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A Systematic Study of Neutron Inelastic
Scattering in the Energy Range
2.0 to 4.5 MeV

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A SYSTEMATIC STUDY OF NEUTRON INELASTIC SCATTERING
IN THE ENERGY RANGE 2.0 TO 4.5 MeV

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A SYSTEMATIC STUDY OF NEUTRON ELASTIC SCATTERING
IN THE ENERGY RANGE 0.0 TO 4.0 MEV

BY

STANLEY ALLEN BRIDGES
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PHYSICAL MONOGRAPHS

The present monograph is devoted to a systematic study of neutron elastic scattering in the energy range 0.0 to 4.0 Mev. The results are presented in the form of a series of tables, each giving the scattering cross-sections for a particular element. The tables are arranged in order of increasing atomic number, and the elements are grouped into three categories: (1) elements with a single stable isotope, (2) elements with two stable isotopes, and (3) elements with three or more stable isotopes. The tables are arranged in order of increasing atomic number, and the elements are grouped into three categories: (1) elements with a single stable isotope, (2) elements with two stable isotopes, and (3) elements with three or more stable isotopes.

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ABSTRACT

Fast neutron inelastic scattering from eighteen elements covering the atomic mass region 27 to 209 has been measured with time-of-flight technique for incident neutrons in the energy range 2.0 to 4.5 MeV. Excitation functions for the population of the individual levels in the nuclei have been derived. The inelastic scattering cross sections have been determined relative to those of the $H(n, n)H$ reaction. Corrections have been applied for the effects of the anisotropic intensity distribution of the neutron source, the attenuation of the neutron flux in the sample as well as the multiple scattering of the neutrons.

The purpose of the work has been to investigate the usefulness of the Hauser-Feshbach statistical model modified according to Moldauer for level width fluctuations and resonance-interference effects in describing the scattering process. Therefore, the relatively large and homogeneous set of experimental neutron inelastic scattering cross sections collected in this work have been compared with those calculated with this model. In making these calculations a knowledge of the proper nuclear potential is necessary. In the present work a local optical potential with the inclusion of a spin-orbit interaction term has been used. The sets of parameters used in the calculations have been taken from a recent investigation on generalized optical model parameters based on experimental neutron elastic scattering data.

The inelastic scattering cross sections calculated with the Hauser-Feshbach-Moldauer model describe in most cases the experimental data well within 20 per cent, with the exception of a few levels in some odd-mass nuclei with collective excited states. In addition comparisons made between calculated and experimental excitation functions have made it possible to determine spins and parities of some levels, for which these quantities previously have been unknown or uncertain.



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1 INTRODUCTION

In 1932 the discovery of the neutron was announced in an article by J. Chadwick [1]. Since that time many experiments have been performed in which the interaction of fast neutrons with various elements has been investigated. These measurements have included the study of elastic as well as nonelastic interactions between atomic nuclei and neutrons. In the present work only investigations of nonelastic processes will be discussed. Such studies are of interest since they can give information on the structure of the atomic nuclei.

During the historical development of this research field up to 1945 a number of experimental techniques were used to study non-elastic interactions between atomic nuclei and neutrons. For instance, the recoil α -particles in an ion chamber as well as the proton recoils in cloud chambers were used to identify the neutrons. Another technique was to use different threshold detectors. However, at that time it was not possible to separate different nonelastic processes with the available experimental facilities. Therefore experimental data regarding nonelastic interactions of fast neutrons from before 1945 are in general not very accurate and accordingly difficult to interpret. Later on, better detectors and neutron sources were soon available and several research groups began using what is now known as the sphere transmission method. In connection with that, different types of neutron detectors were used. Barschall et al. [2, 3], for instance, counted proton recoils in a proportional counter while Gittings et al. [4] and Phillips et al. [5] used threshold detectors. The latter type of detector was also used by Bethe et al. [6 - 9]. They discussed extensively the analysis of the data obtained from sphere transmission experiments and the corrections which had to be applied to them, i. e. corrections for multiple scattering in the spheres, finite source-detector distance, finite size of the detector, absorption in the detector material, angular dependence of the efficiency of the detector and the effect of the energy decrease in elastic collisions. The uncertainties in each of these correction factors of course contributed to the total errors in the final experimental non-elastic cross sections. Thus, the accuracy of the results reflected the uncertainties in the calculations of the different correction factors. The discussion of these corrections by Bethe et al. [6 - 9]

extended the neutron energy range and experimental conditions under which the sphere transmission technique together with threshold detectors could be used. Rosen et al. [10 - 13] successfully used the photographic plate as a detector in neutron nonelastic scattering experiments. This technique is objectionably slow but has the advantage of allowing angular distribution measurements to be made at all chosen angles simultaneously.

The sphere transmission technique discussed above is very useful to gain knowledge of total nonelastic cross sections. At neutron energies lower than the energy of the first excited state of the target nuclei, neutrons can interact nonelastically with atomic nuclei through the capture process and with some nuclei also through the (n, p) and (n, α) processes. However, if the energy of the incident neutrons is higher than the threshold energy of inelastic scattering but lower than the binding energy of a neutron in the target nucleus, the nonelastic process also includes inelastic interactions. At even higher excitation energies (n, Xn) processes are also energetically possible, where X is an integer larger than one.

To obtain information of the yield of the neutrons inelastically scattered to different levels in the target nuclei and not only of the total nonelastic cross section, other experimental methods than those previously mentioned have to be applied. One of these is the detection of the gamma rays produced in the inelastic scattering process. The detection and measurement of gamma rays in early experiments were carried out with Geiger counters and absorbers [14, 15]. A more satisfactory method of gamma ray observation is the use of crystal scintillators together with photomultipliers. The thallium-activated sodium-iodide scintillation crystal was first used by Grace et al. [16]. When using a NaI crystal the background problem due to neutrons is serious, since the neutrons can be captured by I giving rise to gamma-rays or the neutrons can be inelastically scattered by the sodium or iodine nuclei leading to gamma-emission from these nuclei. A useful method for discrimination against such neutron-induced background is the time-of-flight technique which has been used at our laboratory by Holmqvist et al. [17].

The development of the high resolution Ge(Li) detector has essentially improved the quality of the measurements of the gamma-rays emitted in the $(n, n'\gamma)$ reactions. Usually pulsed mono-energe-

tic neutron sources are used in these experiments [18]. To achieve extremely good incident neutron energy resolution pulsed white neutron sources have also been used together with a flight path of about 60 m between the source and the scattering sample [19]. Thus, the energy of the neutrons from the source is determined by time-of-flight technique.

The method of determining the absolute inelastic cross sections by the detection of the gamma rays produced in the inelastic scattering process is in some respects associated with experimental difficulties. This is the case regarding the absolute determination of the neutron flux hitting the investigated sample from the target as well as of the detector efficiency, since the use of rather large samples necessitates the application of corrections for the gamma absorption taking place in the sample. Furthermore, in order to obtain quantitative correlations between the cross sections for gamma production and those for neutron inelastic scattering, a detailed knowledge of the gamma-cascades and the branching ratios is necessary. This is particularly the case when more than a few levels can be excited in the target nuclei.

Inelastic scattering cross sections can also be determined by studying the inelastically scattered neutrons instead of the emitted gamma rays. With this method the population of the different levels in the target nuclei is investigated directly. This can be done by the time-of-flight technique, which was first used by Cranberg et al. [20, 21], who measured the inelastically scattered neutrons from 24 elements at one primary energy, i. e. 2.45 MeV by using a plastic scintillator in optical contact with a photomultiplier as a detector placed 120 to 160 cm from the scattering sample. Since then the same method has been used by many workers. A. B. Smith et al. [22 - 30] have for instance measured neutron inelastic cross sections for several elements with incident neutron energies of 0.3 to 1.5 MeV. Towle et al. [31 - 35] have observed scattering from some elements in the energy range 1 to 4 MeV and Coles et al. [36 - 38] have measured scattering at 1.0 to 5.0 MeV. Further references can be found in CINDA [39]. In this type of measurements the absolute inelastic cross sections are usually determined relative to some standard cross sections, generally those of the $H(n,n)H$ process, which are

known with an accuracy of 1 per cent. Thus, it is enough to measure a quantity which is proportional to the absolute neutron flux and to know the relative efficiency of the neutron detector. The latter quantity can easily be determined with high accuracy by studying the neutrons scattered at different angles from hydrogen in a polythene sample and using the above-mentioned well determined $H(n, n)H$ cross sections.

In connection with starting the use of the neutron time-of-flight technique fast electronics had to be developed and the background problem due to gamma rays as well as room-scattered neutrons had to be solved. The problem with background due to gamma rays has been overcome by the use of organic liquid scintillators with (n, γ) discrimination properties.

2 THE PURPOSE OF THIS WORK

As mentioned in the introduction, several measurements of inelastic neutron scattering cross sections have already been performed with different techniques. However, there is still a lack of a more complete and homogeneous set of experimental material in the energy range investigated in the present work, i. e. 2.0 to 4.5 MeV. Such data can form a good background for the proper understanding of the reaction mechanism and of the usefulness of the nuclear models describing the scattering process. Such knowledge is of interest from a pure nuclear physics point of view as well as in reactor technology. The purpose of this work has been to investigate the usefulness of the Hauser-Feshbach statistical model in describing the scattering process. No attempt has been made to compare the experimental data with the results from calculations with other theories such as the coupled-channel theory.

Neutron scattering experiments, elastic as well as inelastic, demand large amounts of material in the scattering sample to get a large enough neutron yield. Without any supply of enriched isotopes our measuring program had to be designed with regard to elements with natural isotopic compositions. These circumstances have limited our research goal in some respects. The investigations must be limited to elements which have only a few isotopes. Otherwise elements with a large number of levels will give several overlapping neutron

groups which are impossible to resolve with the existing neutron time-of-flight technique. As mentioned in chapter 1 some of these difficulties might be overcome by the use of high resolution Ge(Li) gamma detectors.

In the present work neutron inelastic scattering from eighteen elements, i.e. Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Ga, Y, Nb, In, Pr, Ta, Pb, Pb_r (radiogenic lead) and Bi, has been studied in the energy range 2.0 to 4.5 MeV in steps of 0.25 MeV using high resolution time-of-flight technique. Part of the work has already been reported at Helsinki [40], in Hungary [41] and in Vienna [42] as well as in ref [43].

3 EXPERIMENTAL ARRANGEMENTS

The measurements were performed by using a time-of-flight spectrometer in conjunction with the 6 MV Van de Graaff accelerator. This machine has a klystron bunching system giving pulses of 1 MHz repetition rate and a full width at half maximum of about 1.5 ns [44]. The mean ion current on the target under these circumstances is at maximum about 8 μ A. Fig 1 shows a schematic lay-out of the accelerator and the beam alignment systems.

3.a The electronic apparatus of the time-of-flight spectrometer

The first measurements in the present work were performed with a $\varnothing 4'' \times 2''$ plastic scintillator* in optical contact with a photomultiplier**. In order to improve the signal-to-background ratio in the measurements the plastic scintillator was exchanged for a $\varnothing 5'' \times 2''$ liquid scintillator with pulse shape discrimination properties*** on which a photomultiplier**** was mounted via a light guide with reflector paint on the surface. Fig 2 shows the block diagram of the time-of-flight spectrometer consisting of conventional ORTEC electronics and including (n, γ) discrimination. The spectra were collected in a multi-channel analyser using 1024 channels for each spectrum.

*	NE	104
**	56	DVP/03
***	NE	213
****	RCA	8850

3.b Neutron detector arrangement

The detector was positioned in a shielding consisting of iron, lead and paraffin mixed with lithium carbonate which has been described in ref [45]. The detector and the shielding arrangement were placed on an arm movable on a horizontal circular track with the scatterer positioned on the axis of rotation. Together with the $\varnothing 4'' \times 2''$ scintillator a flight path of 300 cm was used. To be able to use the same shielding arrangement for the $\varnothing 5'' \times 2''$ scintillator the flight path was enlarged to 350 cm.

3.c Neutron sources

Fast monoenergetic neutrons were produced by the $T(p,n)^3\text{He}$ reaction. For the neutron production, gas targets of the type described in ref [46] filled to a pressure of about 1 atm were used. In such a target the nickel entrance window (thickness 2.5 mg/cm^2) was mounted over a 6 mm-diameter hole. As the nickel foil limits the allowable beam current, improvements in the construction of the target cell were made in order to decrease the heating of the nickel foil. Thus the nickel foil was mounted on a gold plate to improve the heat conduction. The gold plate was perforated with holes which made up about 70 per cent of the plate area. This new equipment made it possible to use about a factor of 2.5 higher beam current. Diaphragms having a diameter of 10 mm for the "high current" targets and 6 mm for the other type of target were placed in front of the target cells. The target and the diaphragm were electrically isolated from the beam tube and from each other thus making it possible to measure the current hitting the target as well as that hitting the diaphragm.

In most experiments a target length of 3.0 cm was used but in some cases, where extremely good time-resolution was needed, targets having a length of 1.5 cm were used.

3.d The monitoring of the neutron flux

An absolute determination of the neutron flux hitting the scatterer from the target is a difficult task. Therefore the cross sections have to be determined relative to some well-known standard cross sections. A quantity proportional to the absolute flux was determined by using a direction-sensitive fast neutron monitor. Both

the investigated sample and the standard sample were then irradiated by the same flux. The neutron monitor consisted of a BF_3 -counter enclosed in a large collimating water tank shielding and has been described in ref [47]. The monitor was positioned at an angle of 72° relative to the charged particle beam and at a distance of 300 cm from the target. The long counter was shielded with paraffin at the rear to reduce the background in the measurements. To increase the directionality of the monitor a cylindrical collimator made of paraffin and with an inner diameter of 5 cm was placed in front of the BF_3 -tube. The tankmonitor was frequently calibrated with a Ra-Be source placed at a fixed position in front of the BF_3 -counter.

3.e The scattering samples

The scattering samples of the investigated elements consisted of hollow cylinders placed 10.5 cm in front of the target. The samples used together with the $\varnothing 4'' \times 2''$ scintillator and a flight path of 300 cm had a height of 5.0 cm, an outer diameter of 2.5 cm and an inner diameter of 0.95 cm. In the rest of the experiments, in which the energy resolution was increased and the background was decreased, cylinders having a height of 3.0 cm, an outer diameter of 1.8 cm and an inner diameter of 0.95 cm were used together with the $\varnothing 5'' \times 2''$ liquid scintillator and a flight path of 350 cm.

For the calibration of the detector efficiency described in chapter 4 as well as for cross section comparison measurements, a polythene sample (height 3.0 cm, outer diameter 0.95 cm, inner diameter 0.62 cm) was used.

3.f Contributions to the energy spread of the detected neutrons

There are different sources contributing to the energy spread of the detected neutrons. For instance, the energy loss of the charged particles in the target gas causes an energy spread of the produced neutrons, because the neutron-producing reaction can occur at any place in the target reached by the beam.

The straggling of the charged particle energy, ΔE , in the nickel foil due to fluctuations about the average number of collisions with the atoms of the absorbing material is, according to ref [48], about ± 14 keV for a nickel foil with a thickness of 2.5 mg/cm^2 and with charged particles of such energies as neutrons in the investigated energy region are produced.

A third contribution to the energy spread of the neutrons hitting the scatterer comes from the finite dimensions of the target-scatterer system. This is due to the finite size of the scatterer, the target-scatterer distance and the strong angular dependence of the energy of the neutrons produced by the $T(p,n)^3\text{He}$ reaction.

The energy spread of neutrons of different energies from the target hitting the scatterer is given in Table 1, where the energy loss of the protons in the gas and the straggling of the proton energy in the nickel foil as well as the effect of the finite dimensions of the target-scatterer system have been taken into account.

The thickness of the scintillator will also contribute to the total energy spread of the detected neutrons because a neutron can interact with a proton at any place during its passage through the scintillator. This contribution to the energy spread is for instance ± 0.1 MeV for a 2 MeV neutron and ± 0.2 MeV for a 4.5 MeV neutron when using a scintillator thickness of 5.1 cm.

4 EXPERIMENTAL PROCEDURE

Neutron inelastic scattering from the elements studied were mostly observed at one scattering angle, i. e. 125° . At this angle the $P_2(\cos \theta)$ term in the Legendre polynomial describing the angular distribution is zero. Thus, if the inelastic angular distribution were symmetric around 90° (i. e. only even terms in the Legendre polynomials) and near isotropic then

$$\sigma = 4\pi \frac{d\sigma}{d\Omega} (125^\circ) \quad (1)$$

The validity of these assumptions of the inelastic angular distributions was investigated by observing the differential inelastic cross sections at several angles at 3.0 MeV incident neutron energy. In practice there is a further advantage with choosing 125° . At this angle the elastic differential cross section is near minimum which reduces the interference of the elastic peak with inelastic events.

All cross sections were determined relative to those of neutron scattering from hydrogen. For this purpose, scattering from polythene was measured at 30° at each energy before and after the inelastic scattering experiments, thus giving an opportunity to check the reproducibility of the measurements at the same time. The hydrogen

content in polythene is 14 per cent and in the investigated energy range it is easy to separate the neutrons scattered from hydrogen and carbon at 30° by the time-of-flight technique. The total cross section for the $H(n,n)H$ reaction is, according to Horsley [49], known with an accuracy of one per cent and the scattering is isotropic in the centre-of-mass system for energies less than about 9 MeV. Since the capture cross sections are negligible in the investigated energy range, it can be shown [50] that the differential cross sections can be calculated from the simple formula

$$d\sigma(E_n, \theta)/d\Omega = \pi^{-1} \sigma_T(E_n) \cos \theta \quad (2)$$

where θ is the scattering angle in the laboratory system and $\sigma_T(E_n)$ the total cross section at a primary neutron energy of E_n MeV.

To be able to perform accurate relative cross section measurements, it is important to use a cross section standard with a well known behavior. Furthermore, an accurate determination of the relative efficiency of the detector as a function of energy is necessary. This has been done by measuring neutron scattering from hydrogen at different angles and at different primary neutron energies using a polythene sample. The finite dimensions of the target-scatterer-detector system introduce, however, a spread in the scattering angle of the detected neutrons. This effect together with the fact that the energy of the scattered neutrons is strongly dependent upon the scattering angle makes the $H(n,n)H$ process at large angles less useful for efficiency calibrations. Therefore neutron scattering from hydrogen was only observed at angles smaller than 45° . The detector energy bias was set at about 0.5 MeV in this work, which is shown in Fig 3.

The low energy part of the efficiency curve has been measured by detecting the direct neutrons from the $T(p,n)^3He$ reaction at angles between 20° and 150° and at a proton energy of 3.0 MeV. The relative differential cross sections at $E_p = 3.0$ MeV for this reaction are given with an uncertainty of 4 per cent by A. Paulsen et al. [51].

The energy calibration of the time-to-pulse-height converter of the neutron spectrometer was performed by observing the positions of a large number of peaks corresponding to elastic and inelastic neutron scattering from well-known and well-separated levels in different elements. The positions of peaks obtained by observing neutrons scattering from hydrogen at different angles and energies were

also used for this purpose as well as the positions of the peaks of direct neutrons from the $T(p, n)^3\text{He}$ reaction at different angles at $E_p = 3.0 \text{ MeV}$.

5 THE DATA ANALYSES

The experimental results collected in the time-of-flight measurements were obtained on punched paper tapes from the multichannel analyser. This data was transferred to magnetic tapes at an IBM 360/30 computer on which the normalization of the spectra and the background subtraction were also performed. The spectra were then plotted by hand. The area of a peak representing a certain neutron group in a time-of-flight spectrum was defined as the area under the measured curve limited by the vertical lines through the points of intersection between the time axis and the two tangents of the peak.

The shape of a peak is a function of the corresponding neutron energy and also a weak function of the atomic mass number of the scattering element. The standard shape of the peak at different neutron energies can be found from those spectra having well-resolved peaks. These peaks are then used for the stripping of the unresolved peaks, as shown in Fig 4. The solid line here represents the measured spectrum and the dotted line is the standard peak for this neutron energy normalized to such a height and placed at such a position along the x-axis that after subtraction of this standard peak from the measured curve the rest (the point dashed line) also has the shape of the standard peak at the corresponding neutron energy.

However, the resolution in the time-of-flight spectra was not sufficient to enable individual levels in the residual nucleus to be resolved even with the stripping procedure at all incident neutron energies. Therefore, in those cases cross sections were determined for groups of levels. In some cases even continuous spectra were obtained. These were analysed in energy strips of 0.1 MeV and the number of pulses in each energy interval was calculated.

6 CORRECTIONS

The present measurements of inelastic neutron scattering cross sections have been performed with relatively large samples of the

elements to be investigated. This is due to the comparatively low target neutron flux obtainable in this type of experiment and the small detection solid angle in combination with the relatively small inelastic neutron cross sections. The finite neutron source-sample geometry makes it necessary to apply a number of corrections to the experimental data. Thus the corrected inelastic cross section, σ_{corr} , is obtained from the experimentally determined inelastic cross section, σ_{exp} , by the expression

$$\sigma_{\text{corr}} = \sigma_{\text{exp}} \frac{K(0)/\bar{K} \cdot F/\bar{F} \cdot \text{Out}(E_n) \cdot \text{In}(E_0)}{k} \quad (3)$$

where

$K(0)/\bar{K}$ = the ratio between the correction factors for the anisotropic intensity distribution of the source neutrons calculated for the size of the investigated sample and that of the polythene sample respectively

$F/\bar{F}$ = the correction factor for neutron flux attenuation in the sample

$\text{Out}(E_n)$ and $\text{In}(E_0)$ =
= the correction factors for multiple scattering (out-scattering and in-scattering respectively) in the sample

k = the correction factor for flux attenuation and multiple scattering in the polythene sample

Below the applied corrections will be discussed one by one.

6. a Corrections for the anisotropic intensity distribution of the source neutrons

The correction factor $K(0)/\bar{K}$ for the anisotropic intensity distribution of the target neutrons is introduced as the ratio between the intensity of an isotropic neutron source and the mean intensity of an anisotropic one at the position of the scatterer derived outgoing from the differential cross sections for the reaction. The mathematical expression for this correction factor is derived as follows. Notations are taken from Fig 5. The angle ϕ_{max} is defined as the maximum angle at which neutrons hitting the cylindrical scatterer leave the

target. In the following it is assumed that the differential cross section for the reaction, $\frac{d\sigma(\Phi)}{d\Omega}$, is given by

$$\frac{d\sigma(\Phi)}{d\Omega} = C\Phi^2 + D \quad (4)$$

in the angular region 0° to $\Phi_{\max}$. The mean intensity, $\bar{I}$, of the neutrons at the spherical segment defined in Fig 5 is then given by

$$\bar{I} = \frac{\int_0^{\Phi_{\max}} (C\Phi^2 + D) \sin\Phi \, d\Phi}{b^2 (1 - \cos\Phi_{\max})} \quad (5)$$

By solving this integral the following expression is obtained

$$\bar{I} = \frac{-C[\Phi_{\max}^2 \cos\Phi_{\max} - 2\Phi_{\max} \sin\Phi_{\max} - 2(\cos\Phi_{\max} - 1)] + D(1 - \cos\Phi_{\max})}{b^2 (1 - \cos\Phi_{\max})} \quad (6)$$

The intensity of neutrons, I_0 , at the segment of the sphere assuming an isotropic angular distribution for the neutron producing reaction, i. e. $\frac{d\sigma(\Phi)}{d\Omega} = D$, is given by

$$I_0 = \frac{D \int_0^{\Phi_{\max}} \sin\Phi \, d\Phi}{b^2 (1 - \cos\Phi_{\max})} = \frac{D}{b^2} \quad (7)$$

If the scatterer is a sphere, $I_0/\bar{I}$ is the desired ratio. This quantity is of the order 1.00 to 1.10 and can be written $1 + x$. However, if instead the scatterer is a cylinder with a height h equal to the diameter of the sphere and an outer diameter d , the required ratio is given by

$$I_0/\bar{I} = 1 + \frac{dh}{\pi(\frac{h}{2})^2} x \quad (8)$$

Since the inelastic cross sections in this work are determined relative to those of scattering from hydrogen using a polythene scatterer as mentioned in chapter 4, the value of $I_0/\bar{I}$ is calculated for scatterers of two different sizes, i. e. that of the sample of the investigated element and that of the polythene sample, respectively. The ratio between

those two values will be the correction factor $K(0)/\bar{K}$, which has to be applied to the experimental data in order to take into account the an-isotropic intensity distribution of the target neutrons.

Fig 6 shows the variation of the magnitude of this correction factor as a function of the primary neutron energy calculated for the $T(p,n)^3\text{He}$ reaction and a scatterer with a height of 5.0 cm and an outer diameter of 2.5 cm and a polythene scatterer with the corresponding values 3.0 and 0.95 cm. As shown in the figure the value of this correction factor varies between 1.031 and 1.015 in the energy region investigated in the present work. Therefore, a mean value of 1.023 has been used in the whole region. In those experiments where samples with a height of 3.0 cm and an outer diameter of 1.8 cm have been used together with the polythene sample described above, the corresponding correction is less than one per cent.

6. b Corrections for flux attenuation in the samples

The number of reactions taking place in the scatterer is proportional to the neutron flux in the scatterer. Therefore, corrections for the fact that the flux is different at different places in the scatterer due to neutron attenuation in the sample have to be taken into account. The correction factor is introduced as the ratio between the neutron flux, F , at the place of the centre of the scatterer with no scatterer in position and the mean neutron flux, $\bar{F}$, in the scatterer with the scatterer in position. This correction factor is calculated with the Monte Carlo technique described in ref [52] following 3 neutron groups with 5 000 neutrons in each group. The mathematical expression for this correction factor is derived in ref [52]. Table 2 shows the calculated values of this correction factor at an incident neutron energy of 2.0 MeV using samples with heights of 5.0 cm, inner diameters of 0.95 cm and outer diameters of 2.5 cm.

6. c Corrections for multiple scattering in the samples

Corrections have been applied for the neutron multiple scattering taking place in the samples. These corrections are made in two steps. The first step takes into account the decrease in the number of detected neutrons scattered to a certain nuclear level due to outscattering, i. e. the neutrons which are first scattered to a nuclear level are scattered inelastically once more in the sample and thus

lose a further amount of energy before leaving it. In the second step corrections are applied for inscattering, i. e. for the increase in the number of detected neutrons inelastically scattered to a specific nuclear level due to neutrons which are elastically scattered in one collision before being inelastically scattered to the investigated level. Contributions to the inelastic peak due to elastic-elastic-inelastic events are negligible for scatterers of the sizes used in the present work. Furthermore, no corrections need to be taken into account for inelastic-elastic events because of the almost isotropic angular distributions for inelastic scattering.

It has been shown [53] that the correction factors $\text{Out}(E_n)$ and $\text{In}(E_0)$ for the above mentioned outscattering and inscattering, respectively, are given by

$$\text{Out}(E_n) = \frac{1}{1 - \frac{\sigma_{ne}(E_n)}{\sigma_T(E_n)} (1 - e^{-N\sigma_T(E_n)x})} \quad (9)$$

and

$$\text{In}(E_0) = \frac{1}{1 + \frac{\sigma_{el}(E_0)}{\sigma_T(E_0)} - \frac{Q_{out1}}{1 - Q_{out0}}} \quad (10)$$

where E_n and E_0 are the energies of the detected and incident neutrons, respectively, N is the number of nuclei per unit volume in the scatterer and x is the distance from the first collision point out of the sample in an arbitrary direction. Q_{out0} is the fraction of the incoming neutrons which passes the scatterer without any interaction at all and Q_{out1} the one which leaves the scatterer after one elastic collision. These fractions are calculated with the Monte Carlo technique described in ref [52], where also the physical assumptions for the calculations are given.

6.d Corrections for neutron flux attenuation and multiple scattering in the polythene sample

To avoid the necessity of detailed Monte Carlo calculations to take into account the neutron flux attenuation and multiple scattering in the polythene sample, the tables derived with the approximate pro-

cedure with parallel beam flux attenuation by Cranberg et al. [54] have been used. Cranberg et al. [54] have found this procedure to be particularly simple and accurate where, as here, interest resides primarily in the total elastic scattering cross section. The attenuation factor was calculated assuming scattering from both C and H to be effective in attenuating the neutrons. In order to take into account the divergence of the neutron beam, a geometrical factor has been applied. This factor was obtained by averaging an isotropic flux from a point source positioned in the centre of the target over a rectangular surface having the height and width of the scatterer and was found to be 1.01 for the size of the polythene scatterer used in the present work. The value of this geometrical factor will of course increase with increasing dimensions of the scatterer. Table 3 shows the values of the correction factor k for flux attenuation and multiple scattering in a polythene sample of the dimensions mentioned in chapter 3. e calculated according to Cranberg et al. [54].

7 ESTIMATIONS OF THE TOTAL ERRORS OF THE EXPERIMENTAL CROSS SECTIONS

There are a number of different sources of errors contributing to the total uncertainty in the experimental inelastic cross sections. These sources will here be discussed one by one.

7.a The uncertainty in the determination of the areas of the peaks of the time-of-flight spectra

One of the main sources is the uncertainty in the determination of the areas of the peaks of the time-of-flight spectra. This uncertainty is dependent on the statistical errors in the number of counts, the insufficient resolution in the time-of-flight spectra as well as the continuous background obtained due to neutrons scattered in the room or from the materials of the gas cell as well as to the gammas produced by neutron-reactions taking place anywhere in the room. Such a background is obtained even after the subtraction of the measured background specially when no (n, γ) discrimination was used.

The statistical errors in the number of counts in the analysed peaks were smaller than 3 per cent. The uncertainty due to the con-

the slope of the efficiency curve increases below 1.0 MeV. Therefore, the experimental energy spread of about 50 keV of the neutrons scattered to a certain nuclear level will introduce an increasing uncertainty in the determination of the detector efficiency in this energy region. Thus, at neutron energies of 0.75 MeV, 0.8 MeV and 0.9 MeV the uncertainties introduced by the energy spread of the neutrons are 30 per cent, 20 per cent and 15 per cent, respectively. Due to the large uncertainty factor in the determination of the relative efficiency of the detector below 0.75 MeV, no analyses have been performed for scattered neutrons with lower energies.

7. c The uncertainty in the reference cross sections

The cross sections are, as mentioned in chapter 4, determined relative to those of neutron scattering from hydrogen. The uncertainties of these cross sections are 1.0 per cent according to ref [49] which also contributes to the total error in the experimental data.

7. d The uncertainty in the number of monitor pulses

The statistical errors in the number of monitor pulses during which the measurements have been performed are negligible.

7. e The uncertainties in the different correction factors applied to the experimental data

There are also uncertainties in the different correction factors applied to the experimental results. The uncertainty in the correction factor $K(0)/\bar{K}$ due to the finite geometry of the target-scatterer system is as seen from the formulas in chapter 6, a only dependent on the uncertainty in the shape of the differential cross section curve for the neutron producing reaction. According to chapter 6, a the differential cross section for the $T(p,n)^3\text{He}$ reaction is assumed to be given by

$$\frac{d\sigma(\bar{\Phi})}{d\Omega} = C \bar{\Phi}^2 + D \quad (4)$$

in the angular region 0° to 20° . Outgoing from the differential cross sections given by Perry et al. [55], the ratio C/D has been found to be known with an accuracy of 20 per cent in the energy region investigated in the present work. Calculations have shown that a vari-

ation of 20 per cent in the ratio C/D will introduce a variation of less than 2 per cent in the correction factor $K(0)/\bar{K}$ for the sizes of scatterers used in the present work.

The error in the correction factor for flux attenuation in the sample involves statistical errors introduced by the Monte Carlo method and also uncertainties in the total neutron cross sections used in the calculations. In order to make the statistical errors negligible the correction factors were always calculated by using three groups of neutrons each group containing 5 000 neutrons. The influence of the uncertainty of the total cross section on the correction factor $F/\bar{F}$ can be calculated from the first order power expansion of $F/\bar{F}$ in σ_T , which is given by $F/\bar{F} = a_0 + a_1 N \sigma_T$, where a_0 and a_1 are constants and N is the number of atoms per unit volume in the scatterer. The constant a_0 is determined from the fact that $\lim_{\text{volume} \rightarrow 0} F/\bar{F} = 1$ and the constant a_1 is determined from known values of $F/\bar{F}$ and σ_T . Thus, an uncertainty of 10 per cent in the total cross sections introduces an error of 2 per cent in the correction factor. The uncertainty in the number of nuclei per unit volume is negligible in this connection.

The multiple scattering correction factor also introduces an error mainly due to the uncertainties in the total and elastic neutron cross sections used in the calculation of this correction factor as seen in the formulas given in chapter 6. c. Calculations have shown that uncertainties of 10 per cent in these two cross sections introduce an error of less than 7 per cent in the correction factor.

There are also uncertainties in the correction factors for flux attenuation and multiple scattering in the polythene scatterer calculated according to Cranberg [54]. According to ref [56] an agreement within 2 per cent was obtained for a scatterer with a height of 3.0 cm at a primary neutron energy of 2.5 MeV between the correction factor calculated from Cranberg's tables properly corrected for the divergence of the neutron beam and that one obtained with an ordinary Monte Carlo calculation according to ref [52]. Furthermore, an agreement within 3 per cent was found in ref [57] between the correction factor at 3.98 MeV primary neutron energy calculated from Cranberg's tables and the corresponding one calculated with the computer program MAGGIE using the Monte Carlo technique for a scatterer with a height of 5.0 cm.

The shadow bar which is positioned rather close to the target may, because of its rather large mass, introduce a systematic error in the measurements due to neutrons scattered by the bar before being scattered by the sample in the direction of the detector. However, most of the experimental data is, as mentioned in chapter 4, measured at a detector angle of 125° and in those measurements the neutrons hitting the shadow bar from the target have a much lower energy than those leaving the target in the forward direction because of the strong angular dependence of the energy of the neutrons produced in the $T(p,n)^3\text{He}$ reaction. Furthermore the flight path of the neutrons scattered by the shadow bar before hitting the scattering sample will be longer than that of the neutrons hitting the scatterer directly from the target. Due to these two reasons, these neutrons will only contribute to the part of the spectra corresponding to such low energy that no analysis has been performed. Furthermore, the number of neutrons scattered by the bar before being scattered by the sample in the direction of the detector is also much smaller than that hitting the scatterer in the first collision.

7.f The total uncertainty in the experimental data

Taking into account characteristic values of the different sources of errors a value between 10 and 15 per cent will be obtained for the total error in the inelastic cross section.

7.g Experimental verifications of the applied corrections

In most cases the correction factor for multiple scattering cannot be verified experimentally. However, for Fe it was possible to compare the calculated multiple scattering correction factors for the first excited level with experimental data, while the time-of-flight spectrum for Fe shows a peak apparently corresponding to a level of about 1.75 MeV excitation energy as seen in Fig 7. No such level is known among the iron isotopes and therefore this peak has been identified as due to double inelastic scattering from the strongly excited 2^{+} level at 0.845 MeV. The ratio of the intensity of the peak due to double scattering to that of the one due to single scattering agreed within 2 per cent with that obtained from the calculations.

The validity of the applied corrections for the anisotropic intensity distribution of the source neutrons together with the cor-

rections for flux attenuation and multiple scattering in the samples has been investigated by comparing the corrected inelastic cross sections for Fe obtained with samples of the two different sizes mentioned in chapter 3. e at primary neutron energies of 3.50, 3.75, 4.00 and 4.50 MeV. As shown in Fig 8 and Table 4 the inelastic cross sections obtained with the two different sample sizes agree within the experimental errors.

In order to avoid the application of a correction factor for the anisotropic intensity distribution of the source neutrons, measurements of the elastic angular distributions have been performed with Fe and Bi samples of the same size as that of the polythene sample [58]. After the application of the corrections for flux attenuation and multiple scattering the results from these measurements agree within the experimental errors with those obtained with samples with a height of 5.0 cm, an outer diameter of 2.5 cm and an inner diameter of 0.95 cm as seen in Figs 9 - 10. The latter results have also been corrected for the anisotropic intensity distribution of the source neutrons.

8 SCATTERING THEORY

Many different approaches have been used in order to obtain a theoretical description of the physics behind the nucleon-nucleus interaction. It started about 40 years ago with a first attempt to describe this kind of interaction on the basis of a potential-well model, in which the many-body problem of a nucleon interacting with a complex aggregate of nucleons was replaced by a two-body potential. In this model a rectangular well potential was used. The depth and width of the well specified the strength and range of the interaction. According to the potential-well model, all of the reactions take place by elastic scattering and the neutron cross sections vary slowly and smoothly with energy. However, for slow neutron interactions, it was shown experimentally that resonances appeared in the total cross section which is roughly the sum of the elastic and capture cross sections in this energy range. In order to explain this phenomenon, the compound nucleus concept was introduced by Bohr [59]. In this model one assumes that the incident nucleon interacts very strongly with the target nucleons and that the energy of the incident nucleon is completely shared among all the target nu-

cleons forming a compound nucleus. Such a nucleus may have a lifetime of about 10^{-16} sec, which is long compared with the characteristic value of 10^{-21} sec for the passing time of a 1 MeV neutron through a nucleus and for direct interactions. Thus according to Bohr a nuclear reaction can be described as proceeding in two stages, i. e. the formation of the compound system and the disintegration of the system into the products of the reaction. These two stages are assumed to be independent in the sense that the mode of disintegration of the compound nucleus depends only on its energy, angular momentum and parity, but not on the specific way in which it has been produced.

The occurrence of resonances in total neutron cross section curves can be interpreted on the basis of the compound nucleus model in the following way; The compound nucleus can exist only in quantum states of definite energies, E_s . If E_0 is the energy of the incident nucleon and B the binding energy of that particle to the target nucleus, a compound nucleus can be formed only if $E_0 = E_s - B$. At higher excitation energies of the compound nucleus the resonance levels become broader and start to overlap. This causes the structure from individual resonance levels to disappear at higher energies. As a result of this the cross section curve is smoothed out.

A more general scheme for the description of nuclear reactions than that given by Bohr has been proposed by Weisskopf [60]. He divides the nuclear reaction in three different stages, the independent-particle stage, the compound-system stage and the final stage. The first stage in this scheme can be described by the optical potential model which represents an attempt to amalgamate the potential-well model and the compound nucleus model. This model was introduced in order to give a better description of the experimentally-determined cross section curves. Such a curve can be considered to be the sum of a smooth component from direct reactions and a compound nucleus component, which has individual resonances at low energies and fluctuations at higher ones. According to the optical model the target nucleus acts upon the incident particles as a potential consisting of a real and an imaginary term. The real term accounts for the scattering of the incident wave just as in the potential-well model while the imaginary term accounts for the absorp-

tion. The scattering at this stage is the so-called shape elastic scattering or potential scattering. Absorption here means that the incident particle no longer exists as an independent particle distinct from the target nucleus. This absorption leads to the actual nuclear reaction. Thus an understanding of the first stage of the Weisskopf's description of a nuclear reaction gives information of the total cross section as well as the shape elastic and the absorption cross sections.

There is a close similarity between the nuclear scattering described by the optical model potential discussed above and the scattering of light of a transparent substance. The nucleus can be thought of as a sphere of nuclear matter transmitting, reflecting, refracting and absorbing the incident nucleon waves in the same way as light interacts with the individual atoms or molecules of the transparent substance.

Gradually, refinements of the optical model potential were introduced due to defects in the description of experimental data. Peaslee [61] showed for instance that the experimentally-found transmission through the surface of a nucleus was about a factor of two larger than the one calculated with a rectangular form of the real part of the potential. To get a better description of the experimental results more sophisticated potentials were introduced, which simulated a more transparent nuclear surface. One of the most popular potential shapes used nowadays is the Saxon-Wood potential, in which the diffuseness of the potential well was taken into account [62]. Furthermore, it has been experimentally shown [63] that the scattered nucleons are polarized even with an incident beam of unpolarized particles. In order to account for this effect a spin-orbit term was included in the optical model potential [64]. By the inclusion of such a term the calculated differential shape elastic cross sections for higher angles are increased, thus giving a better agreement with the experimental results.

The second stage of the Weisskopf's description of a nuclear reaction, is called the compound-system stage. This stage includes the formation of a compound nucleus according to Bohr. However, the concept of a compound-system stage is more general than that of compound nucleus formation in that it includes all processes where the particle interacts with the target to a more intimate extent than

can be described by a potential in the entrance channel. The incident particle can for instance interact directly with a target nucleon (direct interaction) or it can set up collective effects such as surface vibrations or nuclear rotations.

The final stage of the Weisskopf's description of a nuclear reaction is the part of the process in which the reaction products are separated from the residual nuclei. Thus the final stage includes the decay of the compound nuclei.

8.a The formalism for the calculations of inelastic neutron scattering cross sections

For medium weight and heavy nuclei it is realistic to consider the inelastic scattering to take place via compound nucleus formation for primary neutron energies below about 5 MeV. According to the previous part of this chapter the first stage of the scattering process is then described by the optical model, on the basis of which it is possible to calculate the total absorption cross section. A statistical model has been proposed by Hauser and Feshbach [65] for the estimation of the distribution of the total absorption cross section between the different decay modes being open at a particular excitation energy of the compound nucleus. This model is based on the following three assumptions:

- 1 The incident particle forms a compound nucleus together with the target nucleus.
- 2 The compound nucleus is formed at such a high excitation energy that its levels are strongly overlapping, i. e. $\Gamma \gg D$ where Γ is the level width and D the level separation. Furthermore, the energy spread of the incident neutrons is much larger than D so that it is possible to excite many states of given quantum numbers for each primary neutron energy. Thus, it is possible to use a statistical average over all available phases among the states in the cross section calculations.
- 3 The mode of decay of the compound nucleus is independent on the way of formation and depends only on the quantum parameters of the system, i. e. the energy, the total angular momentum and the parity, as well as on the spin and parity of the particular decay channel involved.

If these assumptions are fulfilled the inelastic cross section for any decay channel of the compound nucleus can be written as the product of the probability for compound nucleus formation and the probability for decay into a specific state. This is utilized in the following formula for the inelastic cross section given as an energy average of resonant or fluctuating compound-nucleus cross sections according to Hauser and Feshbach [65]

$$\sigma_{aa'} = \pi \lambda^2 \sum_{J, j, l, j', l'} \frac{(2J+1)}{(2i+1)(2I+1)} \frac{T_{a'j'l'}^J T_{ajl}^J}{\sum_{a''j''l''} T_{a''j''l''}^J} \quad (11)$$

where

I = the target nucleus spin

i = the incident particle spin

l, l' = the orbital angular momentum of the incident particle and the emergent one, respectively

j, j' = the channel spins of the incident and emergent particles, respectively ($j = I+i = J-l$ and $j' = J-l'$).

In the formula given above, the term $\pi \lambda^2 T_{ajl}^J$ represents the cross section for compound nucleus formation in the initial channel α represented by the quantum numbers J, j and l , i. e. $\alpha = (a, j, l, J)$. The term $T_{a'j'l'}^J \sum_{a''j''l''} T_{a''j''l''}^J$ represents the probability for the compound nucleus to decay into channel α' with quantum numbers J, j' and l' , i. e. $\alpha' = (a', j', l', J)$. The summation in the denominator is taken over all possible ways in which it is permitted for the compound nucleus to decay when the decay into the channel represented by J, j' and l' can occur. Finally the factor $(2J+1)/[(2i+1)(2I+1)]$ is a statistical weight factor, g_α . With these notations eq (11) can be written as

$$\sigma_{aa'} = \sum_{\alpha\alpha'} g_\alpha \sigma_{\alpha\alpha'}$$

When deriving eq (11) it was assumed that the contribution of each total angular momentum and parity of the system to the average partial reaction cross section could be factored into an average compound-nucleus formation cross section and an independent decay

branching ratio. This assumption enables the use of the transmission coefficients, which are energy averages over resonances with specific angular momenta and parities. However, according to Porter and Thomas [66] the level widths fluctuate in a resonance μ following a Porter-Thomas distribution (e.g. a χ^2 distribution with one degree of freedom), and therefore the assumption of independence of formation and decay of the compound nucleus on the average is no longer valid. Furthermore, it is known that the compound nucleus resonances interfere in a statistically describable manner. Taking these two effects into account a more general expression for the calculation of inelastic scattering cross sections has been derived by Moldauer [67, 68]. With the notations used above he obtained

$$\sigma_{\alpha\alpha'} = \pi\lambda^2 \left\{ \left\langle \frac{\theta_{\mu\alpha} \theta_{\mu\alpha'}}{\theta_{\mu}} \right\rangle_{\mu} - M_{\alpha\alpha'} \right\} \quad (12)$$

where $M_{\alpha\alpha'} = \frac{1}{4} \delta_{\alpha\alpha'}$, $Q_{\alpha} < \theta_{\mu\alpha} >^2$. This expression consists of two terms, the first of which is formally very reminiscent of the Hauser-Feshbach expression whereas the second one, $M_{\alpha\alpha'}$, is a resonance interference term. In this expression for the inelastic cross section the transmission coefficients in the Hauser-Feshbach formula have been replaced by averages over resonance parameters, $\theta_{\mu\alpha}$, where μ denotes the resonance.

$$\langle \theta_{\mu\alpha} \rangle = T_{\alpha}^{\text{comp}} + \frac{1}{Q_{\alpha}} [1 - (1 - Q_{\alpha} T_{\alpha}^{\text{comp}})^{1/2}]^2 \quad (13)$$

The compound-nucleus transmission coefficient, T_{α}^{comp} , is equal to the optical-model transmission coefficient, T_{α} , apart from that portion of the transmitted flux which induces direct reaction processes. Usually T_{α}^{comp} is equal to T_{α} . The choice of the value of the parameter Q_{α} is dependent on the properties of the compound nucleus. If $\Gamma \gg D$, where Γ is the level width and D the level separation, that means that there are many overlapping resonances, the value of Q_{α} goes to zero. In the case of isolated resonances, i.e. $\Gamma \ll D$, Q_{α} approaches one. The amount of deviation of Q_{α} from zero depends on the degree of the repulsion of the neighbouring resonances and on the range of the level correlation effect of this resonance [67].

According to above the transmission coefficients in the Hauser-Feshbach formula has been replaced by averages over resonance pa-

rameters in the Moldauer formula. Therefore the products and ratios of transmission coefficients in the Hauser-Feshbach formula are equivalent to the products and ratios of averages of resonance parameters,

$\frac{\langle \theta_{\mu\alpha} \rangle \langle \theta_{\mu\alpha'} \rangle}{\langle \theta_{\mu} \rangle}$. However, in the Moldauer formula the average is taken over the products and ratios of resonance parameters, $\langle \frac{\theta_{\mu\alpha} \theta_{\mu\alpha'}}{\theta_{\mu}} \rangle$. The assumption in the Hauser-Feshbach theory that

$$\langle \frac{\theta_{\mu\alpha} \theta_{\mu\alpha'}}{\theta_{\mu}} \rangle = \frac{\langle \theta_{\mu\alpha} \rangle \langle \theta_{\mu\alpha'} \rangle}{\langle \theta_{\mu} \rangle} \quad (14)$$

is only valid in the limit where θ_{μ} is not correlated with the values of either $\theta_{\mu\alpha}$ or $\theta_{\mu\alpha'}$, i. e. in the many channel limit where many competing decay channels are available so that fluctuations of the level widths about their average values, can be neglected.

8. b Nuclear optical model potential

For the performance of the Hauser-Feshbach calculations transmission coefficients are necessary. These can be calculated by using a local spherical optical model potential of the form

$$-V(r) = Uf(r) + iWg(r) + U_{SO} \left(\frac{\hbar}{\mu_{\pi} c} \right)^2 \frac{1}{r} \frac{d}{dr} \left[f(r) \right] \bar{\sigma} \cdot \bar{\ell} \quad (15)$$

The real and imaginary parts of the potential are described by $Uf(r)$ and $Wg(r)$ with the functions $f(r)$ and $g(r)$ expressing the radial variations. A spin-orbit interaction term is also included with the potential depth U_{SO} , the Pauli spin and angular momentum operators $\bar{\sigma}$ and $\bar{\ell}$, respectively, and the pion mass μ_{π} . The radial shapes of the real and imaginary parts of the potential are described by the Saxon-Woods and derivative Saxon-Woods form factors

$$f(r) = \{1 + \exp [(r-R_U)/a]\}^{-1} \quad (16)$$

and

$$g(r) = 4 \{1 + \exp [(r-R_W)/b]\}^{-2} \exp [(r-R_W)/b] \quad (17)$$

where $R_U = r_{0U} A^{1/3}$ and $R_W = r_{0W} A^{1/3}$ are the radii, and a and b the diffuseness parameters.

8. c Continuous spectra of inelastically scattered neutrons

In such cases where there are so many open channels available for compound nucleus decay that both the compound and residual nuclei can be considered to be in the continuous region, it is interesting to study the shape of the continuous spectra obtained in order to test statistical models describing the level densities in nuclei. Observations of inelastic neutron scattering is then a very useful method for obtaining information concerning nuclear level density variations with excitation energy and mass number because over the incident energy range from less than half a MeV to more than 7 MeV the (n, n') reaction predominates and the most probable mechanism is expected to be compound-nucleus formation. On the contrary, for charged particle scattering the Coloumb barrier effects would considerably restrict the energies and nuclei for which observations of continuous spectra are easily interpretable.

The energy distribution of the neutrons emitted from an excited nucleus in its continuum region shows a general resemblance to the distribution of energy among the molecules of a gas in thermal equilibrium. With such a picture in mind the emission of particles from a nucleus can be compared with the evaporation of molecules from a liquid drop. Therefore, the excited nucleus may be looked upon as a thermodynamic system at a certain temperature. Continuing this resemblance the nuclear entropy and the nuclear level density at an excitation energy E^* may according to ref [69] be related by the formula

$$S(E^*) = \ln \omega(E^*) \quad (18)$$

Furthermore, the temperature, T , may be defined as in statistical thermodynamics by the formula

$$\frac{1}{T} = \frac{\partial S}{\partial E^*} \quad (19)$$

These definitions of temperature and level density can be used in the formula for the shape of the spectrum of emitted neutrons according to the reciprocity theorem [69]

$$N(E) = \text{const } E \omega(E^*) \sigma_{n^*}(E, E^*) \quad (20)$$

where

E^* = the excitation energy of the residual nucleus
 E = the energy of the emitted neutron
 $N(E)$ = the number of emitted neutrons having an energy E
 $\sigma_{n^*}(E, E^*)$ = the inverse cross section, i.e. the cross section for the formation of the compound nucleus by the emitted neutron and the excited residual nucleus.

If this formula is used together with a Taylor series expansion of the nuclear entropy for the residual nucleus and the definition of the nuclear temperature given above, the following expression for the energy distribution of the emitted neutrons is obtained

$$N(E) = \text{const } E \exp(-E/T) \sigma_{n^*}(E, E^*) \quad (21)$$

If the inverse cross section is assumed to be independent of the energy this expression is equivalent to the Maxwellian distribution.

If $\frac{\partial S}{\partial E^*}$ is constant over the range of E^* considered, T will be a constant for a specific spectrum. However, in general the nuclear temperature is a function of E^* .

The general formula for the energy distribution of the emitted neutrons is independent of the nuclear model. However, the values of the nuclear temperatures can be used to test different statistical models for the description of the excited levels of the nucleus. From a certain model a relation can be obtained between the excitation energy of the nucleus and the temperature, that is $E^* = E^*(T)$. According to the Fermi-gas model, for instance, $E^* \sim T^2 = a' T^2$. Therefore $S(E^*) = \int \frac{dE^*}{T} = 2(a' E^*)^{1/2} + \text{const}$, $\omega(E^*) = \text{const } (E^*)^{-2} \exp[2(a' E^*)^{1/2}]$ and

$$N(E) = \text{const } E (E^*)^{-2} \exp[2(a' E^*)^{1/2}] \sigma_{n^*}(E, E^*) \quad (22)$$

Thus from measurements of the energy distribution of the emitted neutrons in the continuum region the level density constant a' can be determined.

9. NUMERICAL CALCULATIONS OF NEUTRON INELASTIC CROSS SECTIONS

As mentioned in chapter 8. b the transmission coefficients, which are necessary for the Hauser-Feshbach calculations of inelastic neutron cross sections, are calculated using the spherical local optical potential given in eq (15). The values of the optical model parameters used in the present work are taken from a recent investigation by Holmqvist and Wiedling [70] on generalized optical model parameters based on elastic scattering experimental data for about the same elements as have been studied in the present work. In that work the parameters r_{0U} , r_{0W} and a were found to be essentially independent of the neutron energy within the range considered, i. e. 1.5 to 8.0 MeV. Therefore the mean values of these parameters for each element have been used to obtain the mass dependence, which for r_{0U} and r_{0W} can be represented by linear expressions

$$r_{0U} = 1.183 + 0.0003A \quad (23)$$

$$r_{0W} = 1.183 + 0.0004A \quad (24)$$

The parameter a was found to be both mass and energy independent within the precision of the measurements. Taking all measurements into account a mean value of 0.66 ± 0.01 fm was obtained for this parameter.

In order to avoid the well known ambiguity of U due to its dependence on r_{0U} , the volume integral J_U of the real central potential has been used to study the mass number dependence instead of U itself. Thus the quantity $J_U U/A = (4\pi U/A) \int_0^\infty f(r)r^2 dr$ was calculated for all elements and neutron energies of the five parameter analyses. These $J_U U/A$ values have been found to be essentially independent of the neutron energy for each element. Accordingly the mean values of $J_U U/A$ for individual elements have been used to calculate the mass dependence which is given by the expression

$$J_U U/A = 475.2 - 0.658A + 0.001A^2 \quad (25)$$

The imaginary potential depth has been treated in a similar way to the real potential depth. Thus the quantity $J_W W/A = (4\pi W/A) \int_0^\infty g(r)r^2 dr$ was calculated. Since this integral is also essentially independent of the neutron energy for each element, mean values of $J_W W/A$ have been used to obtain the mass dependence which is expressed by

$$J_W W/A = 103.4 - 0.301A \quad (26)$$

Generalized values of the real and imaginary potential depths are obtained by solving the equations of $J_U U/A$ and $J_W W/A$ by using the above mentioned expressions for r_{0U} and r_{0W} , the value previously given for a and a value for b of 0.48 fm.

The numerical values of the potential parameters U , W , r_{0U} and r_{0W} used in the present work are given in Table 5.

Besides a knowledge of the optical model potential the Hauser-Feshbach calculations also require a knowledge of the level properties of the target nucleus. In some cases spins and parities of high-lying levels are unknown and cannot be determined in the present work. However, the distribution of the values of spins and parities among the levels is calculated by applying a method derived by J. Eriksson [71]. This method, which primarily was derived for the calculation of level densities, is based on the counting of excited shell model states.

The calculations of the transmission coefficients and the inelastic neutron scattering cross sections have been performed with the ABACUS-NEARREX computer program [72]. For those nuclei, in which more than 25 levels are excited at the higher incident neutron energies used in the present work, the Hauser-Feshbach calculations of the inelastic cross sections have been performed with another program [73] using the transmission coefficients calculated with ABACUS-NEARREX. In those cases, where the excited levels of the nuclei are very close-lying at higher excitation energies and thus the last mentioned method for the calculation of the inelastic cross sections have been used, the levels in different excitation energy intervals have been grouped according to spin and parity. Thus, the number of levels for which the transmission coefficients have to be calculated has been reduced without changing the cross sections for the lower lying levels more than one per cent. All the Moldauer calculations have been performed with ABACUS-NEARREX.

10 RESULTS

The experimental excitation functions representing the cross sections for fast neutron transitions to the individual levels of the investigated elements are shown in Figs 11 to 26. The corresponding theoretical excitation curves representing cross sections calculated with the Hauser-Feshbach (HF) formalism (solid lines) and the Moldauer (MHF) formalism (dashed as well as point dashed lines) are also shown in the same figures. The dashed lines have been obtained assuming many overlapping levels in the compound nucleus (i. e. $Q_{\alpha} = 0$ according to chapter 8. a) while the point dashed lines have been calculated assuming isolated resonances (i. e. $Q_{\alpha} = 1$). The cross section values refer in most cases to 100 per cent abundance of the isotopes. Exceptions are those for Ti, Cr and Ga as well as those for two groups of levels in Ni, which refer to these elements in their natural isotopic compositions. These exceptions are due to the fact that scattering to levels in the different isotopes of these elements cannot be separated in the present work. The experimental errors indicated include all contributions discussed in chapter 7.

Comparisons between calculated and experimental excitation functions make it possible to determine spins and parities of the levels. Thus for such levels for which these quantities are unknown or uncertain and for which experimental cross sections have been determined in the present work, calculations have been performed with several spin and parity assignments to these levels. The spin and parity values recommended in this work will then be the ones which give the best theoretical description of the experimental excitation functions. This procedure has been applied, for instance, to the 1.19 MeV level in Co and the 2.22 MeV level in Y.

As mentioned in chapter 4 the differential inelastic cross sections have been measured at several angles at 3.0 MeV incident neutron energy for most of the elements studied in the present work in order to investigate the shape of the angular distributions. For Al, angular distributions for the different levels have been measured also at some incident neutron energies above 3.0 MeV. The results from these measurements are given in Figs 27 to 34 showing that all the distributions except those for the 2.73 MeV level in ^{27}Al are isotropic or slightly anisotropic but symmetric around 90° . The curves have been fitted by the method of least squares using Legendre

polynomial expansions of the form $d\sigma(\theta)/d\Omega = \sum_l B_l P_l(\cos \theta)$. The highest term necessary in these expansions was the P_2 -term. However, in all cases the P_1 coefficients were so small that the excitation cross sections obtained by angle-integration of the Legendre expansions differed only slightly (less than 5 per cent) from those calculated on the basis of the differential cross sections at 125° (see chapter 4). The inelastic excitation functions shown in Figs 11 to 26 have been obtained by applying the latter procedure. The only exception is the experimental excitation function for the 2.73 MeV level in Al, since as mentioned above the angular distributions for this level were found to be slightly anisotropic as shown in Fig 34.

The experimental inelastic scattering cross section data for the individual elements will be discussed below one by one and in chapter 10. q the results from the measurements of the continuous spectra of inelastically scattered neutrons will be presented. A more general discussion of the systematic trends of the results will be given in chapter 12.

10. a Aluminium

The excitation functions for neutron inelastic scattering to individual levels in aluminium are given in Fig 11 and Table 6. The cross sections are given for the levels having excitation energies up to 3.0 MeV. The excitation functions show in general a smooth variation with the incident neutron energy except for the two first excited states for which some structure is observed at incident neutron energies of 2.77 and 3.78 MeV. For comparison the time-of-flight spectra for Al are plotted at three incident neutron energies, viz. 2.50, 2.77 and 3.01 MeV, in Fig 35.

The experimental data has been compared with cross sections calculated according to chapter 8. a. It is seen that the best agreement between experimental and calculated cross sections is obtained with $Q_\alpha = 0$ indicating many overlapping levels in the compound nucleus according to MHF. However, the resonance structure effects already pointed out for the first two excited levels could obviously not be described by the HF or MHF formalisms, since the conditions for this model are not fulfilled.

10.b Titanium

The experimental and calculated inelastic cross sections for Ti in the energy range 2.0 to 3.25 MeV are given in Fig 12 and Table 7. Since scattering to the levels in the different isotopes composing the natural element, i. e. $^{46-50}\text{Ti}$ cannot be separated in the present work, the cross sections are given for groups of levels and for the natural isotopic composition of the element. The level schemes for the different titanium isotopes are taken from refs [74 - 76].

The experimental data for the group composed of the first 2^+ states in ^{46}Ti and ^{48}Ti with excitation energies of 0.889 MeV and 0.983 MeV, respectively, are very well described by the results obtained with the MHF formalism using $Q_\alpha = 0$. This formalism also gives a good description of the experimental data for the group of 5 levels with a mean excitation energy of 1.57 MeV. The largest contribution to the inelastic cross sections of this group of levels is due to the excitation of the 1.55 MeV 2^+ level in ^{50}Ti (about 50 per cent of the calculated cross sections) while the remaining 50 per cent corresponds to the excitation of four levels, viz. the 1.542 MeV $11/2^-$, 1.585 MeV $3/2^-$ and 1.622 MeV $9/2^-$ levels in ^{49}Ti as well as the 1.549 MeV $3/2^-$ level in ^{47}Ti .

The experimental inelastic cross sections for the group with a mean excitation energy of 1.36 MeV composed of 3 levels, viz. 1.247 MeV $9/2^-$ in ^{47}Ti , 1.382 MeV $3/2^-$ in ^{49}Ti and 1.442 MeV $11/2^-$ in ^{47}Ti , are best described by the calculated curve obtained with the MHF formalism using $Q_\alpha = 0$. However, this curve is still about 50 per cent higher than the experimental data.

For the group with a mean energy of 1.77 MeV composed of 4 levels, viz. 1.723 MeV $1/2^-$ and 1.762 MeV $5/2^-$ in ^{49}Ti and 1.793 MeV $1/2^-$ and 1.821 MeV $3/2^+$ in ^{47}Ti , as well as for the 2.010 MeV 4^+ level in ^{46}Ti the inelastic neutron cross sections are only measured at incident neutron energies of 3.0 and 3.29 MeV, while for each of the groups at mean energies of 2.24 and 2.46 MeV the cross sections are only measured at 3.29 MeV incident neutron energy. Thus, no more detailed conclusions can be drawn about the extent of agreement between experimental and theoretical results for these four groups. The main contribution (about 80 per cent) to the calculated cross sections for the group at 2.24 MeV is due to scattering to the 2.295 MeV 4^+ level in ^{48}Ti , while the remaining 20 per cent is due to the excitation of the 2.161 MeV $3/2^-$ and the

2.256 MeV $3/2^-$ levels in ^{47}Ti as well as the 2.262 MeV $7/2^-$ level in ^{49}Ti . Furthermore, scattering to the 2.421 MeV 2^+ level in ^{48}Ti gives the largest contribution (about 95 per cent) to the calculated cross sections for the peak at an excitation energy of 2.46 MeV, while the remaining 5 per cent is due to the excitation of the 2.360 MeV $1/2^+$ and 2.414 MeV $1/2^-$ levels in ^{47}Ti as well as of the 2.470 MeV $1/2^+$, 2.504 MeV $1/2^+$, 2.506 MeV $15/2^-$ and 2.516 MeV $7/2^-$ levels in ^{49}Ti .

10.c Vanadium

The excitation functions for neutron scattering to the different levels in V up to an excitation energy of 3.0 MeV are shown in Fig 13 and Table 8. From the decay of ^{51}Cr [77] levels have been observed at excitation energies of 0.47 and 0.63 MeV. However, no peaks have been observed in the time-of-flight spectra due to neutrons scattered to these levels.

Inelastic scattering from V has been studied earlier at our laboratory [78]. Since the experimental conditions as regards the time resolution and the position of the energy cut-off of the detector were improved in the present study, new measurements on this element were performed. The results from the two different measurements agree within the experimental uncertainties. No angular distributions were measured in the present work, since these were found isotropic in the earlier measurements.

The experimental excitation functions are well described by the cross sections calculated according to MHF with the correlation parameter $Q_\alpha = 0$ indicating many overlapping levels in the compound nucleus. However, for the group composed of the 2.675 MeV $3/2^+$ and the 2.699 MeV $15/2^-$ levels the experimental cross sections are about 30 per cent lower than the calculated ones. At incident neutron energies above 3.5 MeV the cross sections calculated with the pure HF formalism describe the experimental data well.

10.d Chromium

Due to the low natural abundances of ^{50}Cr and ^{54}Cr (4.3 and 2.4 per cent, respectively) neutron inelastic cross sections are only reported in the present work for the strongly excited 2^+ states at

0.783 and 0.835 MeV, respectively, in these isotopes. No cross sections have been determined for the levels in ^{53}Cr . In the main isotope ^{52}Cr neutron scattering cross sections have only been determined for the first excited level. The excitation energy of the second level in this isotope is according to ref [76] 2.370 MeV. Neutrons scattered to this level cannot be resolved from those scattered to two levels in the less abundant ^{53}Cr isotope. Therefore, no excitation function is reported for this level in the present work.

The experimental results are shown in Fig 14 and Table 9, where the cross sections are given for the natural abundances of the isotopes. The experimental results for the 1.434 MeV level in ^{52}Cr are well described by the cross sections calculated according to MHF with the parameter $Q_{\alpha} = 0$ in the energy range 2.0 to 3.25 MeV. For higher energies the ordinary HF calculations describe the experimental data best. On the other hand the experimental excitation function for the group consisting of the 0.783 MeV level in ^{50}Cr and the 0.835 MeV level in ^{54}Cr are very well described by the cross sections calculated with the MHF formalism with the parameter $Q_{\alpha} = 1$.

10.e Manganese

The measured and calculated neutron inelastic scattering excitation functions for ^{55}Mn are given in Fig 15 and Table 10. For the four lowest excited levels in ^{55}Mn the MHF calculations with the parameter $Q_{\alpha} = 0$ give good descriptions of the experimental data up to a primary neutron energy of 2.5 MeV. At higher energies the experimental excitation functions for these levels as well as for the fifth excited state agree well with those calculated with the pure HF formalism. The spins and parities of the levels used in these calculations are given both in Fig 15 and Table 10. The good agreement between experimental and calculated cross sections for the first four excited levels confirms the spin assignments to these levels of Barrows et al. [18]. For excitation energies higher than 2.0 MeV only the energies of the levels are known, while spins and parities have to be estimated as described in chapter 9. With the chosen level properties which are given in Fig 15 and Table 10 the experimental data for the group of levels with a mean energy of 2.40 MeV composed of states at 2.365 MeV $7/2^{-}$, 2.398 MeV $9/2^{-}$

and 2.425 MeV $11/2^-$ is in good agreement with the cross sections calculated with the HF formalism. The same is valid for the group at 2.79 MeV including the 2.726 MeV $7/2^-$, the 2.751 MeV $9/2^-$, the 2.823 MeV $11/2^-$ and the 2.874 MeV $3/2^-$ levels as well as for the one consisting of nine levels between 2.954 and 3.129 MeV. However, the calculated cross sections for the group composed of five levels between 2.197 and 2.311 MeV as well as for that one including the 2.564 MeV and the 2.582 MeV levels are, in some cases, more than a factor of 2 higher than the experimental data. In order to decrease the disagreements between the experimental and calculated cross sections for these two last-mentioned groups of levels, calculations were performed with lower spin values of the composing levels. Thus in these calculations the group of levels with a mean excitation energy value of 2.26 MeV included two levels with $I^\pi = 1/2^-$, two levels with $I^\pi = 3/2^-$, and one level with $I^\pi = 5/2^-$ while the group at 2.57 MeV included one level with $I^\pi = 1/2^-$ and one with $I^\pi = 3/2^-$. The spins and parities of the other levels remained unchanged. With these spin assignments the experimental data for the groups of levels at 2.26 and 2.57 MeV are better described by the calculated cross sections, while instead, disagreements are obtained for the groups of levels at 2.40 and 2.79 MeV, respectively. However, since the number of excited states with unknown spins and parities are relatively high and the excitation functions are only determined for groups of levels, the spins and parities of the individual levels cannot be determined unambiguously.

10.f Iron

In the present work neutrons which have been scattered to the levels in the most abundant isotope ^{56}Fe were observed as well as such which have been scattered to the 1.410 MeV 2^+ level in ^{54}Fe . The results are shown in Fig 16 and Table 11. The experimental data in the energy range 2.0 to 3.5 MeV for the 0.845 MeV level in ^{56}Fe as well as the 1.410 MeV level in ^{54}Fe appears to lie roughly half way between the curves calculated according to MHF with the parameter Q_α equal to 0 and 1, respectively. The need of a non-zero value of the parameter Q_α to describe the experimental data indicates the necessity of using modified transmission coefficients. For the 1.410 MeV level one has to observe that the errors are estimated

to be 25 per cent due to the low natural abundance of the ^{54}Fe isotope. This makes it more difficult to draw any conclusions regarding which value of the correlation parameter Q_α gives the best agreement between experimental and calculated data. At primary neutron energies higher than 3.5 MeV the inelastic cross sections for the 0.845 MeV and the 1.410 MeV levels calculated according to the pure HF formalism describe the experimental data well. However, above 4.0 MeV the experimental cross sections are larger than the calculated ones. For instance, at 4.5 MeV the calculated cross sections are about 30 per cent lower than the experimental data. These discrepancies can be due to a small contribution of direct interaction as also has been suggested by Kinney et al. [79]. Furthermore, the cross sections calculated with $Q_\alpha = 0$ agree well with the experimental results for the 2.085 MeV 4^+ and the 2.658 MeV 2^+ levels as well as for the group related to the 2.94 MeV 0^+ and the 2.957 MeV 2^+ levels in the energy range up to 4.0 MeV. Above 4.0 MeV the best description of the cross sections for these levels as well as for the group composed of the 3.119 MeV 1^+ and the 3.122 MeV 4^+ levels are obtained with the pure Hauser-Feshbach formalism. The cross section for the group including the 3.368 MeV 2^+ , the 3.388 MeV 6^+ , the 3.445 MeV 3^+ and the 3.450 MeV 1^+ levels has only been determined at one neutron energy, i. e. 4.5 MeV. At this energy the experimental and HF calculated results agree within 20 per cent.

The angular distributions of the inelastic neutron cross sections for the different levels at 3.02 MeV incident neutron energy are observed to be isotropic within the experimental errors as shown in Fig 30.

10.3 Cobalt

The excitation functions for the levels up to 1.744 MeV in Co are given in Fig 17 and Table 12. Experimental results are obtained for primary energies in the region 2.0 to 3.5 MeV. The uncertainty in the analysis of the first three levels at 1.100, 1.190 and 1.291 MeV, respectively, increases with increasing primary energy due to limited time resolution of the time-of-flight spectrometer. Therefore, the analysis of the separate levels was confined to incident neutron energies below 3.5 MeV.

The knowledge of the excited levels above 2.0 MeV in Co is mainly limited to the energies, while the spins and parities have

to be estimated. No spin assignments to these levels can be made in the present work since, as mentioned above, excitation functions have only been determined for levels up to 1.744 MeV. The estimation of spins and parities of these levels will of course introduce some uncertainties in the cross sections calculated according to the HF as well as to the MHF formalisms. For the 1.190 MeV level, calculations with three alternative values of I^π , i. e. $5/2^-$, $7/2^-$ and $9/2^-$, have been performed, since all these spin assignments to this level are possible according to ref [80]. The change of the spin of this level will not affect the cross sections of the other levels to any extent. As seen in the figure, good agreement is obtained with $I^\pi = 7/2^-$. The cross sections calculated with the MHF formalism as well as those for the other levels calculated with the HF as well as the MHF formalisms and shown in the figure, are those obtained with this spin assignment to the 1.190 MeV level. The experimental data for the 1.100 MeV level in the energy region 2.0 to 2.5 MeV are well described by the cross sections calculated according to Moldauer with the parameter $Q_\alpha = 0$, while at higher incident neutron energies cross sections calculated with the HF formalism agree well with the experimental data. For the rest of the levels, i. e. the 1.190 MeV $7/2^-$, the 1.291 MeV $3/2^-$ and the 1.744 MeV $7/2^-$ levels as well as the group including the 1.434 MeV $1/2^-$, the 1.463 MeV $7/2^-$ and the 1.482 MeV $5/2^-$ levels, good agreement is obtained in the whole investigated energy range between the experimental data and the cross sections calculated with the pure HF formalism.

10. h Nickel

Excitation functions have been determined only for levels in the isotopes $^{58, 60, 62}\text{Ni}$ and not for those in the less abundant ones, i. e. $^{61, 64}\text{Ni}$. The experimental and theoretical excitation functions in the energy range 2.25 to 3.25 MeV are shown in Fig 18 and Table 13. At neutron energies above 3.25 MeV the time-of-flight spectra become more complex due to the mixture of isotopes and to the increasing number of exit channels in each isotope making the analysis of the cross section data difficult.

The cross sections for the 1.172 MeV 2^+ state in ^{62}Ni , the 1.333 MeV 2^+ state in ^{60}Ni , the 1.454 2^+ state in ^{58}Ni as well as

for the 2.158 MeV 2^+ state in ^{60}Ni are given for 100 per cent abundances of the isotopes, while those for the group including the 2.286 MeV 0^+ level in ^{60}Ni , the 2.303 MeV 2^+ level in ^{62}Ni and the 2.340 MeV 4^+ level in ^{62}Ni as well as those for the 2.459 MeV 4^+ level in ^{58}Ni together with the 2.506 MeV 4^+ level in ^{60}Ni are given for the natural isotopic composition of the element. The cross sections for the first excited 2^+ states in ^{58}Ni , ^{60}Ni and ^{62}Ni are of the same magnitude. However, due to the large differences in isotopic abundance the peak due to neutrons scattered to the 1.172 MeV 2^+ level in ^{62}Ni is rather small compared with the peaks due to scattering to the 1.333 MeV 2^+ level in ^{60}Ni and the 1.454 MeV 2^+ level in ^{58}Ni , respectively.

The excitation functions calculated according to MHF with $Q_\alpha = 0$ for the 1.172 MeV, the 1.333 MeV, the 1.454 MeV and the 2.158 MeV levels describe the experimental data well in the investigated energy region. At a primary neutron energy of 3.25 MeV experimental results are also obtained for a group of levels including the 2.286 MeV level in ^{60}Ni and the 2.303 and 2.340 MeV levels in ^{62}Ni as well as for a group consisting of the 2.459 MeV level in ^{58}Ni and the 2.506 MeV level in ^{60}Ni . The cross sections for these groups calculated with HF taking into account the natural abundance of the different isotopes agree well with the experimentally determined data.

The angular distributions of the cross sections for the first four levels are isotropic at an energy of 3.02 MeV (Fig 31).

10.i Copper

The experimental excitation functions for the 0.670 MeV and the 0.962 MeV levels in ^{63}Cu as well as for the 0.771 MeV and the 1.115 MeV levels in ^{65}Cu are shown in Fig 19 and Table 14 together with the theoretical cross sections calculated with the HF as well as with the MHF formalisms. Due to the mixture of the two isotopes in the natural element and to the increasing number of levels at higher excitation energies, no excitation functions have been determined for any levels above 1.115 MeV.

For primary neutron energies below 2.75 MeV the cross sections calculated according to the MHF formalism with the parameter $Q_\alpha = 0$ give a good description of the experimental data, while for

higher primary energies the agreement between the experimental data and the cross sections calculated with the pure HF formalism is very good.

10.j Gallium

The experimental excitation functions in the energy range 2.0 to 3.25 MeV for levels in Ga are shown in Fig 20 and Table 15 together with those calculated with the HF and the MHF formalisms. Natural gallium is composed of 60.2 per cent ^{69}Ga and 39.8 per cent ^{71}Ga . Since neutron groups belonging to levels in the two isotopes cannot be separated, the cross sections are given for groups of levels for the natural element. The level schemes used are compilations from refs [81 - 83].

In the investigated energy interval the cross sections calculated with $Q_{\alpha} = 0$ give the best description of the experimental data for all excited levels. Thus, the MHF calculated and the experimental cross sections for the group composed of the 0.872 MeV level in ^{69}Ga and the 0.911 MeV and 0.965 MeV levels in ^{71}Ga as well as for the group composed of the 1.027 MeV and 1.108 MeV levels in ^{69}Ga and the 1.108 MeV level in ^{71}Ga agree within 20 per cent. However, the cross sections for the remaining investigated groups of levels at 0.35, 0.52, 1.36 and 1.50 MeV, respectively, calculated with MHF are as much as 50 per cent higher than the experimental data. These deviations will be further discussed in chapter 12.b.

10.k Yttrium

The experimental and theoretical excitation functions in the neutron energy region 2.0 to 4.0 MeV for the excited states in ^{89}Y are shown in Fig 21 and Table 16. The calculated cross sections for the 0.900 MeV $9/2^{+}$ level are almost a factor of 2 larger than the experimental data. The spin and parity of this state are well determined by Shure et al. [84] and Goldhaber et al. [85], since they have established the M4 character of the 0.900 MeV isomeric transition to the ground state. As in the present work Shafroth et al. [86] have found an unsatisfactory agreement between the experimental data for this level and the HF calculated cross sections.

The experimental results for the 1.51 MeV $3/2^{-}$ level as well as those for the 1.74 MeV $5/2^{-}$ level agree well with those

calculated according to MHF with $Q_{\alpha} = 0$ in the whole investigated energy region.

For the 2.22 MeV level two values of I^{π} have been suggested, viz. $5/2^{+}$ and $7/2^{+}$, [87]. As shown in the figure the best agreement between calculations and experiments is obtained with $I^{\pi} = 7/2^{+}$. Thus, this will be the spin assignment to this level suggested in the present work and the calculated cross section values given in the figure for the other levels are obtained with this spin and parity assignment.

10.1 Niobium

The experimental as well as the MHF and HF predicted excitation functions for levels up to an excitation energy of 1.71 MeV are shown in Fig 22 for primary neutron energies in the region 2.0 to 3.5 MeV. The experimental results are also given in Table 17. Due to the large amount of excited states in the ^{93}Nb isotope the MHF calculated cross sections are at most 15 per cent lower than those calculated with HF in the whole investigated energy region. Furthermore, Fig 22 shows that the calculated cross sections are about a factor of two larger than the experimental ones for some of the investigated levels, viz. for the groups composed of levels at 0.686 and 0.744 MeV, at 0.809 and 0.810 MeV, at 0.950 and 0.979 MeV, at 1.29, 1.297, 1.316, 1.335, 1.364 and 1.395 MeV and at 1.57 and 1.605 MeV as well as for the single level at 1.083 MeV. For the group composed of the 1.485, 1.491 and 1.501 MeV levels an agreement within 50 per cent is obtained between the experimental and calculated cross sections, while the corresponding figure for the group including the 1.665, 1.67, 1.683 and 1.71 MeV levels is 25 per cent.

The excited states of ^{93}Nb have during recent years been studied by several workers [23, 38, 88 - 93]. Inelastic neutron scattering has thereby been observed [23, 38, 88 - 91] as well as single particle transfer reactions [92] and Coulomb excitation reactions [88, 93]. The spin and parity of the ground state ($9/2^{+}$) and the first excited state ($1/2^{-}$) are well established and in accordance with shell model predictions with the 41st proton in a $1g_{9/2}$ state for the ground state and with a proton in the $2p_{1/2}$ shell being paired with the proton in the $1g_{9/2}$ shell giving $I^{\pi} = 1/2^{-}$ for the first excited state. Furthermore, the $7/2^{+}$ spin and parity assignment to the 0.744

MeV level is also well established, while the proposed assignments to the other levels differ considerably. However, the level scheme of ^{93}Nb given in ref [94] has been used in the calculations for the present work. The spins and parities of those levels, for which these values are not given in ref [94], are taken from ref [91] except the spins and parities of six levels between 1.75 and 3.25 MeV, which have been estimated.

10.m Indium

The spins and parities of the ground state as well as of the two first excited states of ^{115}In at 0.336 and 0.597 MeV, respectively, are well established according to ref [95] to be $9/2^+$, $1/2^-$ and $3/2^-$, respectively. The excitation functions for the two first excited levels are shown in Fig 23 and Table 18. Due to ref [96] levels up to an excitation energy of 2.208 MeV are known. No information of higher-lying levels has been found in the literature. Therefore, decay-channel competition would be deficient and thus the calculated results would become too large at primary neutron energies above 2.21 MeV. That is the reason why HF and MHF calculations have only been performed in the energy range 2.0 to 2.25 MeV in the present work. The results of the performed calculations agree within the experimental uncertainties with the experimental data for the first excited state, while the calculated cross sections for the second excited state are as much as a factor of two higher than the experimental results.

As mentioned above, discrepancies between experimental and calculated cross sections have been found for the second excited state at 0.597 MeV with $I^\pi = 3/2^-$. This state is according to ref [95] likely a mixture of the $2p_{3/2}$ proton-hole state in terms of the spherical shell-model and the $3/2^-$ member of the multiplet obtained from coupling of the 2^+ excitation of the even core to the $p_{1/2}$ hole state. This will be further discussed in chapter 12.b.

10.n Praseodymium

The experimental and calculated neutron inelastic scattering cross sections for levels in ^{141}Pr with excitation energies below 1.9 MeV are given in Fig 24 and Table 19. Since no excitation levels with energies higher than 2.8 MeV seem to have been published in

the literature, the decay-channel-competition would be deficient and thus the calculated cross sections too large at neutron energies higher than 2.8 MeV. Therefore, no calculations have been performed at energies above 3.0 MeV. Good agreement is obtained up to this energy for the group composed of the 1.292 MeV $5/2^+$ and the 1.299 MeV $1/2^+$ levels as well as for the group at 1.47 MeV including the 1.435 MeV $3/2^+$, the 1.450 MeV $3/2^+$, the 1.455 MeV $7/2^+$, the 1.493 MeV $5/2^+$ and the 1.520 MeV $1/2^+$ levels. However, for the first excited 0.145 MeV $7/2^+$ state the calculated cross sections are about a factor of 2 higher than the experimental ones, while the calculated values for the group composed of the 1.118 MeV $11/2^-$ and the 1.128 MeV $3/2^+$ levels are between 20 and 50 per cent higher than the experimental data. On the other hand the calculated cross sections for the group at 1.61 MeV including the 1.578 MeV $5/2^+$, the 1.607 MeV $3/2^+$ and the 1.649 MeV $1/2^+$ levels are about 30 per cent lower than the experimental ones. For the group at 1.82 MeV composed of four levels between 1.783 and 1.856 MeV the calculated and experimental cross sections at 2.75 MeV agree within 10 per cent. No further conclusions can be drawn about the agreement since this is the only experimental point below 3.0 MeV, the energy at which the calculations were stopped.

10.0 Lead

Scattering from two different lead samples have been studied in this experiment. One of the samples consisted of natural lead, while the other one was made of radiogenic lead which is composed of 88.2 per cent ^{206}Pb , 8.8 per cent ^{207}Pb and 3.0 per cent ^{208}Pb . The results for the 0.803 MeV 2^+ , the 1.165 MeV 0^+ , the 1.341 MeV 3^+ and the 1.460 MeV 2^+ levels in ^{206}Pb are shown in Fig 25 and Table 20 together with the results for the 0.570 MeV $5/2^-$ and the 0.894 MeV $3/2^-$ levels in ^{207}Pb as well as the 2.615 MeV 3^- level in ^{208}Pb .

The results obtained with the different scatterers agree within the experimental errors. The uncertainties in the cross sections obtained with the radiogenic lead sample for the levels in ^{206}Pb are generally smaller than those obtained with the sample made of natural lead due to the isotopic compositions of the samples. For the same reason the results for the levels in ^{207}Pb obtained by the

sample made of natural lead have smaller errors than those obtained with the radiogenic lead sample. For ^{208}Pb results have only been obtained with the natural sample.

Rather good agreement (within 25 per cent) is obtained between the experimental data and the cross sections calculated with the MHF formalism with $Q_{\alpha} = 0$ for the ^{206}Pb and ^{207}Pb levels for primary energies from 2.0 to 3.0 MeV except for the 0.894 MeV $3/2^{-}$ level in ^{207}Pb , for which the calculations overestimate the experimental data by as much as a factor of 2 for the lowest energies. At higher primary energies the ordinary HF calculations give a very good description of the results for the 0.894 MeV $3/2^{-}$ level in ^{207}Pb as well as for the 1.165 MeV 0^{+} level, the 1.341 MeV 3^{+} level and the 1.460 MeV 2^{+} level in ^{206}Pb . The calculated cross sections for the 0.570 MeV $5/2^{-}$ level in ^{207}Pb and for the 0.803 MeV 2^{+} level in ^{206}Pb are for some energies as much as 25 per cent lower than the experimental data.

For the 2.615 MeV 3^{-} level in ^{208}Pb , which according to Lane and Pendlebury [97] is an octupole collective oscillation state only three experimental points have been determined in the present work. These agree within about 30 per cent with the cross sections calculated with the HF formalism.

10.p Bismuth

The experimental and theoretical excitation functions for Bi are shown in Fig 26 and Table 21. Poor agreement between experiment and theory is obtained at primary neutron energies below 3.5 MeV. At higher energies the cross sections calculated with the ordinary HF theory describe the experimental data well for the 0.897 MeV $7/2^{-}$ and the 1.609 MeV $13/2^{+}$ levels. In the same energy region, agreements within 25 per cent are obtained between the experimental and calculated cross sections for the group with a mean excitation energy of 2.58 MeV consisting of six levels, viz. the 2.492 MeV $3/2^{+}$, the 2.563 MeV $9/2^{+}$, the 2.582 MeV $7/2^{+}$, the 2.599 MeV $11/2^{+}$, the 2.601 MeV $13/2^{+}$ and the 2.616 MeV $5/2^{+}$ levels. Furthermore, the calculated cross sections for the group composed of the 2.741 MeV $15/2^{+}$, the 2.822 MeV $5/2^{-}$ and the 2.827 MeV $7/2^{-}$ levels are as much as a factor of 2 higher than the experimental results.

Also Cranberg et al. [98] noted that the calculated cross sections at 2.5 MeV were too high, if the parameters obtained by fitting the theoretical angular distribution to the experimental one for only elastically scattered neutrons were used. In their work, account was therefore taken of the compound elastic as well as the inelastic scattering in bismuth when determining the optical model parameters. In carrying out that procedure the weights of the inelastic cross sections were multiplied by a factor of 10 to augment their effect in determining the best final fit, which then was quite good.

10.g Results from the measurements of the continuous spectra of inelastically scattered neutrons

As mentioned in chapter 8. c only neutrons scattered to the lowest lying excited states are resolved in the time-of-flight spectra for some of the investigated elements, e. g. In and Ta. The continuous neutron spectra obtained for these elements were (as described in chapter 8. c) divided into energy intervals of 0.1 MeV. The number of pulses, $N(E)$, was determined in each of these intervals centred on E equal to the mean energy of the scattered neutrons in the interval. Figs 36 to 42 show the plots of $\ln[N(E)/E]$ versus E for the inelastically scattered neutrons from In and Ta. All energies are converted to the centre-of-mass system from the original data in the laboratory system. Eq (21) which represents the continuous spectra of inelastically scattered neutrons in terms of a nuclear temperature, seems to be quite useful to describe the experimental data for In and Ta at excitation energies higher than 2.55 and 1.65 MeV, respectively. The values of the temperature parameter T obtained from least square fits to the experimental data in the energy regions corresponding to these excitation energy ranges are given in Table 22.

The multiple scattering, which takes place in the scattering samples due to their sizes should increase the number of low-energy neutrons observed compared to the true spectra. Therefore, corrections calculated according to chapter 6. c have been applied to the experimental data. Within an uncertainty of ± 5 per cent no differences in the temperatures were noted for the spectra obtained for In and Ta due to the application of these corrections.

As mentioned in chapter 8. c the Fermi gas model gives an expression of the form of eq (22) for the energy distribution of the emitted neutrons. To test this expression plots of $\ln[E^{*2} N(E)/E]$ versus $E^{*1/2}$ for In and Ta are shown in Figs 43 to 49. The values of the parameter a' obtained from least square fits to the experimental data are given in Table 22.

The results of the present work have been compared to those of Thomson [99], who has studied the continuous spectra of fast neutrons scattered inelastically from several elements at incident neutron energies ranging from 4.0 to 7.0 MeV. The temperatures obtained for In in the present work, which was performed under better experimental conditions, agree well with those reported by Thomson as seen in Fig 50. For Ta Thomson has only reported a measurement at 7.0 MeV. Thus, it is difficult to draw any conclusions about the agreement with the results of the present work.

According to Thomson [99] the value of the parameter a' can be calculated from the formula

$$a' = E_{av}^* (1/T + 2/E_{av}^*)^2 \quad (27)$$

where E_{av}^* is given by

$$E_{av}^* = E_0 - 2T \quad (28)$$

T is the temperature obtained at the incident neutron energy E_0 . For In the agreement between calculated and experimental values of a' is better than 12 per cent as seen in Table 22, while the agreement for Ta is better than 20 per cent.

11 COMPARISONS BETWEEN THE PRESENT EXPERIMENTAL NEUTRON INELASTIC SCATTERING CROSS SECTIONS AND PREVIOUSLY REPORTED ONES

There are only a few comprehensive studies of neutron inelastic scattering cross sections reported previously. In the early work by Cranberg et al. [21] cross sections have been measured for the excited levels in 24 elements at one single primary neutron energy, i. e. 2.45 MeV. Furthermore, as already mentioned in the introduction, A.B. Smith et al. [22 - 30] have published results from

studies of neutron inelastic scattering cross sections in the energy region 0.3 to 1.5 MeV for several elements. In other energy ranges below 5 MeV there are no such systematic studies reported previously. Thus there are only a few cross section measurements, the results of which can be compared with those of the present work. The references to these measurements are given in Table 23 together with the techniques used and the energy ranges covered. As seen in the table the most comprehensive measurements in the energy range of interest in this work, i. e. 2.0 to 4.5 MeV, are those of Towle et al. [31 - 35]. They have observed scattering from five of the elements (i. e. Al, V, Fe, Ni, Y) at a number of energy points in the interval from 1 to 4 MeV. In the following the results of the comparisons between the present experimental results and those reported in the references given in Table 23 for the same energy interval will be discussed.

11. a Aluminium

Comparisons with the high resolution gamma ray production cross sections reported by Voss et al. [19] have only been made for the first two excited levels at incident neutron energies below 3.2 MeV, where no cascading from higher excited levels is possible. In this energy range the agreement with the cross sections determined in the present work is excellent. Our experimental results also agree within the experimental errors with those of Towle et al. [31] at ten different neutron energies except for the 2.73 MeV level at a primary neutron energy of 4.0 MeV, for which their cross section is high by about 25 per cent. However, Towle et al. could not separate the 0.842 and 1.013 MeV levels because of insufficient energy resolution. Thus comparisons have only been made with their cross sections for the group composed of these two levels. These quantities are consistent within the experimental errors with those of this work, except at 4.0 MeV where their cross section is about 30 per cent higher than ours.

11. b Vanadium

Good agreement is obtained between our results and those reported by Towle [34] at a number of energy points for the first

six excited levels. On the other hand the cross sections obtained at four primary neutron energies by Barrows et al. [18] for the 0.930, 1.609 and 1.813 MeV levels are nearly a factor of two higher than those of the present work, while the results for the 0.320 and 2.41 MeV levels agree within the reported uncertainties.

11.c Chromium

Neutron inelastic scattering from Cr has previously been studied by Broder et al. [100]. They have determined cross sections for the 1.434 MeV level in ^{52}Cr at 0.1 MeV intervals from 1.6 to 3.0 MeV. The results are consistent with ours.

11.d Manganese

The cross sections reported by Barrows et al. [18] for the first four excited states in Mn at primary neutron energies of 1.83 and 2.21 MeV are in agreement with those of the present work.

11.e Iron

Our experimental cross sections for the first two excited states in ^{56}Fe compare favorably with those deduced from the measurements at a number of primary neutron energies of Gilboy and Towle [32]. Furthermore, the cross sections reported by Hopkins et al. [101] for the first excited state at six energy points are consistent within 25 per cent with the data of this work at primary neutron energies below 4.0 MeV, while the corresponding figure is 70 per cent at 4.5 MeV. For the group composed of the 2.94 and 2.957 MeV levels the cross sections obtained in the two measurements are in agreement within the experimental errors. Furthermore, the results of Hopkins et al. for the 2.085 MeV level as well as for the group of states including the 3.119 and 3.122 MeV levels are systematically higher than ours by about 50 per cent. The corresponding figure for the 2.658 MeV level is about 25 per cent.

11.f Cobalt

The cross sections reported by Guenther et al. [102] at about twenty different primary neutron energies agree within the quoted experimental errors with those of this work for all the investigated levels.

11.g Nickel

The experimental results obtained by Towle et al. [33] at a number of energy points for the 1.333 MeV level in ^{60}Ni and the 1.454 MeV level in ^{58}Ni compare favorably with ours. In addition our cross sections for these two levels as well as for the 2.158 MeV level in ^{60}Ni agree within the experimental errors with those of Broder et al. [100]. Finally our excitation functions for the 1.172 MeV level in ^{62}Ni , the 1.333 MeV level in ^{60}Ni and the 1.454 MeV level in ^{58}Ni extrapolated to lower primary energies also seem to be consistent with those reported by Rogers et al. [103] from threshold up to 1.8 MeV.

11.h Yttrium

The experimental cross sections obtained in the present work for the 0.900 MeV and the 2.22 MeV levels agree within the experimental errors with those reported by Shafroth et al. [86] at fourteen energy points in the range from 0.98 to 3.36 MeV, while the results for the 1.51 MeV and the 1.74 MeV levels are about 30 per cent lower than those reported by them. In addition our cross sections for the 0.900, 1.51 and 1.74 MeV levels are consistent within 30 per cent with those given by Towle et al. [35] at eight energy points in the range 2.0 to 3.5 MeV, while at higher primary energies the results of the two measurements agree within the quoted errors.

11.i Niobium

Coles [38] has measured neutron inelastic scattering from Nb at 0.2 MeV intervals between 1.0 and 3.0 MeV and at 0.5 MeV intervals up to 5.0 MeV. His results for the group composed of the 0.686 and 0.744 MeV levels as well as for the group including the 0.809 and 0.810 MeV levels differ considerably from those obtained in the present work. However, the sums of the experimental cross sections for those two groups of levels obtained in the two measurements agree within the quoted uncertainties. Coles pointed out that there is considerable overlap of these two groups in his spectra, which can explain the discrepancies. The results for the other levels are consistent within the given experimental errors.

With a few minor exceptions the cross sections determined in this work also compare favorably with those deduced from the

neutron measurements of Smith et al. [104] at 0.1 MeV intervals from 1.8 to 4.0 MeV. Furthermore the cross sections obtained by Rogers et al. [103] from threshold up to 1.8 MeV are consistent with ours extrapolated to lower energies. Exceptions are their results for the group including the 0.686 and 0.744 MeV levels at 1.69 and 1.79 MeV primary neutron energies, which seem to be considerably higher than ours.

11.j Praseodymium

The experimental results at a number of energy points reported by Malan et al. [105] for the group composed of the 1.118 and 1.128 MeV levels are about 40 per cent higher than our data, while the corresponding figure for the group including the 1.292 and 1.299 MeV levels is 30 per cent. In addition, the cross sections deduced from the measurements by Tanaka et al. [106] at five different energies for the group composed of the 1.118 and 1.128 MeV levels compare favorably with those of this work, while the results for the 0.145 MeV level are consistent within 40 per cent.

11.k Lead

Neutron inelastic scattering from Pb has been studied earlier by Cranberg et al. [98] at 0.25 MeV intervals from 2.0 to 5.0 MeV. Their results for the investigated levels in ^{206}Pb and ^{207}Pb compare favorably with ours within the experimental uncertainties.

11.l Bismuth

The experimental cross sections obtained in the present work for the first excited level in Bi are about 30 per cent lower than those reported by Tanaka et al. [106] at four energies below 3.5 MeV, while at this energy the results agree within the quoted experimental uncertainties. For the second excited level the agreement between the two measurements is good except at 3.0 MeV, where our result is 30 per cent lower than the one reported by Tanaka et al..

The experimental cross section given by Cranberg et al. [98] for the first excited level in Bi at a primary neutron energy of 2.5 MeV is about 20 per cent larger than ours, while the agreement for the second excited level is very good.

12 DISCUSSION

In chapter 10 the results of the neutron inelastic scattering measurements have been compared with those calculated with the Hauser-Feshbach (HF) formalism properly adjusted according to Moldauer (MHF) for one element at a time. The transmission coefficients used in these calculations have been obtained using a set of optical model parameters as described in chapter 9. The inelastic cross sections calculated in this way describe in most cases the experimental data well within 20 per cent. Exceptions are a few levels in some odd-mass nuclei with collective excited states. These exceptions will be further discussed in chapter 12.b. It is obvious from chapter 10 that in those cases where there are few open competing decay channels for the compound nucleus, the cross sections calculated with the MHF formalism with $Q_{\alpha} = 0$ as a rule give the best description of the experimental data. The only exceptions found are the cross sections for the group composed of the 0.783 MeV level in ^{50}Cr and the 0.835 MeV level in ^{54}Cr , which are best described by MHF calculations with $Q_{\alpha} = 1$, as well as the experimental cross sections for the 0.845 MeV level in ^{56}Fe and the 1.410 MeV level in ^{54}Fe , which are found to lie roughly in between those calculated with $Q_{\alpha} = 0$ and $Q_{\alpha} = 1$.

From the curves given in Figs 11 to 26 it is clear that the inelastic cross sections calculated with the MHF formalism with $Q_{\alpha} = 0$ are lower than those calculated with the HF formalism by at most 45 per cent at the lowest primary neutron energy. This figure decreases when the number of open decay channels for the compound nucleus increases with increasing primary neutron energy. Thus with for instance 17 open channels, the cross sections calculated according to MHF with $Q_{\alpha} = 0$ are less than 20 per cent lower than those calculated with the HF formalism. In the present work the MHF calculations with $Q_{\alpha} = 0$ have been performed up to such an incident neutron energy that the MHF corrections are less than 10 per cent.

In the following the experimental inelastic scattering data and the appurtenant theoretical calculations will be discussed separately for the even-even nuclei and for the odd-mass nuclei. Furthermore the compound elastic cross sections calculated with the HF and MHF formalisms will be discussed outgoing from the re-

sults for the inelastic scattering as well as the sensitivity of the calculated inelastic cross sections to changes in the optical model parameters.

12. a Inelastic scattering cross sections for the excited states in even-even nuclei

There are several even-even nuclei among the isotopes from which inelastic neutron scattering has been studied in the present work. These isotopes are $^{46, 48, 50}\text{Ti}$, $^{50, 52, 54}\text{Cr}$, $^{54, 56}\text{Fe}$, $^{58, 60, 62}\text{Ni}$ and ^{206}Pb . For the first 2^+ levels in ^{54}Fe , ^{56}Fe , ^{50}Cr and ^{54}Cr good descriptions of the experimental data for primary neutron energies between 2.0 and 3.25 MeV are obtained with the Moldauer formalism using modified transmission coefficients ($Q_\alpha \approx 1/2$ for the iron isotopes and $Q_\alpha = 1$ for the chromium isotopes). For the first 2^+ levels in the remaining isotopes the cross sections calculated with unmodified coefficients ($Q_\alpha = 0$) give the best agreement with the experimental data. According to chapter 8. a the need to use $Q_\alpha = 1$ in the MHF formalism in order to theoretically describe the experimental data indicates that there are isolated resonances in the compound nucleus, while $Q_\alpha = 0$ indicates many overlapping levels. At primary neutron energies higher than 3.25 MeV the cross sections calculated with the pure Hauser-Feshbach formalism describe the experimental data well. However, above 4.00 MeV there is a tendency for the cross sections for the first 2^+ levels in ^{52}Cr , ^{54}Fe and ^{56}Fe calculated with the HF formalism to underestimate the experimental data. Thus for the 0.845 MeV 2^+ level in ^{56}Fe and the 1.410 MeV 2^+ level in ^{54}Fe the calculated cross sections are about 30 per cent lower than the experimental data at a neutron primary energy of 4.5 MeV, while for the 1.434 MeV 2^+ level in ^{52}Cr the calculated value at the same primary energy is about 25 per cent lower than the experimental one. These discrepancies between experimental and calculated cross sections can be due to the fact that the inelastic neutron cross sections in this energy region may be composed of small direct interaction contributions superposed on the compound nucleus contributions. This explanation has been proposed for ^{56}Fe by Kinney et al. [79] and might also be valid for the other isotopes.

Scattering has also been observed to some higher lying 2^+ states in the studied even-even nuclei, viz. the 2.957 MeV and the 3.368 MeV states in ^{56}Fe , the 2.158 MeV state in ^{60}Ni and the 1.460 MeV state in ^{206}Pb . Furthermore scattering to the following 4^+ states have been observed, viz. 2.085 MeV and 3.122 MeV in ^{56}Fe , 2.459 MeV in ^{58}Ni , as well as to the following 0^+ states, viz. 2.94 MeV in ^{56}Fe and 1.165 MeV in ^{206}Pb . Finally scattering has been observed to the 3.119 MeV and the 3.450 MeV 1^+ states in ^{56}Fe , the 3.388 MeV 6^+ state in ^{56}Fe as well as to the following 3^+ states, viz. the 3.445 MeV state in ^{56}Fe and the 1.341 MeV state in ^{206}Pb . For all these states the cross sections calculated with $Q_\alpha = 0$ give the best description of the experimental data. Thus an agreement within 15 per cent is obtained between the MHF calculated cross sections and the experimental data.

12.b Inelastic scattering cross sections for the excited states in odd-mass nuclei

For most of the investigated odd-mass nuclei, i. e. ^{27}Al , ^{51}V , ^{55}Mn , ^{59}Co , $^{63,65}\text{Cu}$ and ^{207}Pb , good agreement is obtained between experimental and calculated cross sections as mentioned in chapter 10. However, for some of the levels in $^{69,71}\text{Ga}$, ^{89}Y , ^{93}Nb , ^{115}In and ^{209}Bi the calculated cross sections differ with as much as a factor of 2 from the experimental results.

In order to explain the discrepancies mentioned above the nuclear structure of the different isotopes will be discussed. In general odd-mass nuclei can be looked upon as a single nucleon outside an even-even core. De Shalit [107] has pointed out the possibility of describing some of the excited states of such nuclei in terms of the excitation of the even-even core. Then, if the excited states of the even-even core are collective in nature, the corresponding excited states of the odd-even nuclei will be collective to the same extent. This type of collective excited states can be found in all the odd-mass nuclei mentioned above, for which there are disagreements between experimental and calculated inelastic cross sections. Thus certain features of the structure of $^{89}_{39}\text{Y}_{50}$ might according to ref [86] result from coupling of the 39th $p_{1/2}$ proton to excited states of the $^{88}_{38}\text{Sr}_{50}$ core, which have been shown to be collective in nature

to some extent. For ${}^{93}_{41}\text{Nb}_{52}$ it has been proposed [91] that the five excited levels 0.744 MeV $7/2^+$, 0.809 MeV $5/2^+$, 0.950 MeV $13/2^+$, 0.979 MeV $11/2^+$ and 1.083 MeV $9/2^+$ can be considered to form an excited core multiplet resulting from the coupling of a $1g_{9/2}$ proton to the 2^+ one-phonon state of ${}^{92}_{40}\text{Zr}_{52}$, i.e. to a vibrational core formed by the remaining 40 protons and 52 neutrons. Furthermore, levels in the odd-mass Ga isotopes can according to ref [81] be looked upon as an odd proton in various single-particle orbits coupled to the ground state or to some collective vibrational modes of the even-even Zn cores. This assumption of a collective core in Ga nuclei is supported experimentally in refs [108 - 110], where the strong ground-state γ -transitions from the levels at 0.574, 0.872, 1.108 and 1.334 MeV in ${}^{69}\text{Ga}$ suggest that these states contain large contributions from a $p_{3/2}$ particle coupled to the 2^+ core excitation.

Furthermore, the six levels 2.492 MeV $3/2^+$, 2.563 MeV $9/2^+$, 2.582 MeV $7/2^+$, 2.599 MeV $11/2^+$, 2.601 MeV $13/2^+$ and 2.616 MeV $5/2^+$ in ${}^{209}_{83}\text{Bi}_{126}$ together with the 2.741 MeV $15/2^+$ level results from coupling of an $h_{9/2}$ proton to the 3^- octupole excited state in ${}^{208}\text{Pb}$ according to ref [111].

Finally the 0.597 MeV $3/2^-$ level in ${}^{115}_{49}\text{In}_{66}$ is according to ref [95] likely to be a mixture of the $2p_{3/2}$ proton-hole state and the $3/2^-$ member of the multiplet obtained from coupling of the 2^+ excitation of the ${}^{116}_{50}\text{Sn}_{66}$ core to the $p_{1/2}$ hole state. According to the same reference the ground state and the 0.336 MeV $1/2^-$ state are well described as the $1g_{9/2}$ and $2p_{1/2}$ states of a single hole in the $Z = 50$ shell. According to ref [112] some of the levels with excitation energies above 0.6 MeV are rotational in nature.

In the Hauser-Feshbach as well as the Moldauer formalisms, wave functions for single-particle nuclear states are used. However, it is clear that all the odd-mass isotopes discussed above have collective states in the investigated excitation energy region. Therefore, this can be a possible explanation of the discrepancies between calculated and experimental cross sections for some of the levels in these isotopes.

12. c The compound elastic cross sections calculated with the HF and MHF formalisms

The results of this systematic study of inelastic scattering cross sections are also of great interest to the study of elastic scattering cross sections, since the HF and MHF calculations give, in addition to the inelastic cross sections, also the compound elastic cross sections. The latter quantity is not directly measurable but is part of the experimentally-observed elastic cross section. The use of the HF and MHF formalisms make it possible to estimate the compound elastic contribution and thus correct the experimental angular distributions for this effect before the distributions are compared with the shape elastic cross sections calculated with the optical model. Therefore it is of importance to know the effect of the Moldauer corrections on the calculated compound elastic cross sections. A comparison between the cross sections calculated with the MHF formalism with $Q_{\alpha} = 0$ and those calculated with the HF formalism are most interesting in this connection since it has been found in this work that the inelastic cross sections calculated with the MHF formalism with $Q_{\alpha} = 0$ give the best agreement with the experimental data.

For compound elastic scattering, contrary to inelastic scattering the cross sections calculated with $Q_{\alpha} = 0$ in the MHF formalism are always larger than those calculated with the HF formalism. Furthermore the ratio between the compound elastic cross sections calculated with those two formalisms increases with increasing incident neutron energy in the investigated energy range and thus with an increasing number of open decay channels for the compound nucleus. With about 15 open channels this ratio varies between 1.4 and 2.4 for the investigated elements. This is in agreement with the variation of this ratio between 1.0 and 3.0 found by Moldauer [68] and with the calculations of Satchler [113], which show that this ratio increases with an increasing number of open decay channels for the compound nucleus. Furthermore the results from the calculations performed in the present work show that the ratios obtained for the odd-mass nuclei are all lower than those for the even-even nuclei.

12. d The sensitivity of the calculated cross sections to changes in the optical model parameters

As mentioned above and in chapter 9, sets of optical model parameters have been used in the present work to calculate the trans-

mission coefficients, which then are used in the HF and MHF calculations. These parameters have been derived from a systematic study of elastic scattering angular distributions for about the same elements as have been studied in the present work. Thus it is of interest to investigate the sensitivity of the inelastic cross sections to changes in the optical model parameters one at each time in comparison with the accuracy with which the HF and MHF formalisms have been found to calculate the cross sections as well as with the magnitude of the ratio between cross sections calculated with the HF and MHF formalisms. In order to investigate this problem HF calculations have been performed for some characteristic elements at 3.0 MeV primary neutron energy with changes in the different parameters one at each time. These calculations have shown that the inelastic cross sections are rather insensitive to changes up to 10 per cent in the values of W and r_{0W} as shown in Tables 24 and 25, in which the calculated inelastic cross sections for the different states in Fe at 3.0 MeV are given. However, as shown in Tables 26 and 27, where also calculated cross sections for Fe are given, the sensitivity to changes in U and r_{0U} is higher. This is specially the case for the cross sections for the higher-lying excited states. However, changes of U with ± 5 per cent will affect the inelastic cross sections for the levels from which the neutrons are scattered with an energy larger than 0.3 MeV with less than 10 per cent. Furthermore, changes in r_{0U} with ± 5 per cent will affect the cross sections with less than 5 per cent except for the levels from which the neutrons are scattered with an energy lower than 1.0 MeV. Finally, variations of the diffuseness parameter a of ± 5 per cent will also influence the value of the inelastic cross sections by less than 10 per cent (Table 28).

Since the used set of optical model parameters are derived from a systematic study of elastic scattering, it is also of interest to know the sensitivity of the elastic angular distributions to changes in the different parameters. Thus a change in the real potential depth, U , will shift the whole angular distribution for elastic scattering along the angular axis. This shift is quite observable with a change of ± 5 per cent in the parameter value. A quite observable shift is also obtained by changing the real radius parameter, r_{0U} , by ± 2 per cent. By changing the imaginary potential depth, W , or the imaginary radius parameter, r_{0W} , the depths of the minima and the heights of the maxima are varied. Thus changes of the optical model

parameters of such orders that, as mentioned above, the size of the inelastic cross section is affected by more than 10 per cent give quite observable effects in the calculated elastic angular distributions. Therefore it is quite satisfactory to use parameters derived from elastic scattering measurements for the calculations of the inelastic cross sections.

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Table 1

The different contributions to the energy spread of the target neutrons hitting the scatterer.
Target pressure = 1 atm, the diameter of the particle beam = 1.0 cm, thickness of the foil = 2.5 mg/cm²

Neutron producing reaction	Primary neutron energy (MeV)	Target length (cm)	The dimensions of the scatterer		Neutron energy spread due to			Total ener- gy spread (MeV)
			height (cm)	outer dia- meter (cm)	the proton energy loss in the tar- get (MeV)	the stragg- ling in the nickel foil (MeV)	the finite dimensions in the tar- get scatter- er system (MeV)	
T(p,n) ³ He	2.0	3.0	5.0	2.5	± 0.038	± 0.014	± 0.026	± 0.048
		1.5	5.0	2.5	± 0.019	± 0.014	± 0.026	± 0.035
		3.0	3.0	1.8	± 0.038	± 0.014	± 0.012	± 0.042
		1.5	3.0	1.8	± 0.019	± 0.014	± 0.012	± 0.026
	4.0	3.0	5.0	2.5	± 0.024	± 0.014	± 0.046	± 0.054
		1.5	5.0	2.5	± 0.012	± 0.014	± 0.046	± 0.050
		3.0	3.0	1.8	± 0.024	± 0.014	± 0.021	± 0.035
		1.5	3.0	1.8	± 0.012	± 0.014	± 0.021	± 0.028

Table 2

The calculated values of the correction factor $F/\bar{F}$ for flux attenuation in the investigated elements at an incident neutron energy of 2.0 MeV using samples with heights of 5.0 cm, inner diameters of 0.95 cm and outer diameters of 2.5 cm.

Ele- ment	Al	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Ga	Nb	Pb	Pbr	Bi
F/ $\bar{F}$	1.16	1.21	1.26	1.22	1.26	1.26	1.24	1.28	1.26	1.15	1.26	1.21	1.20	1.17

Table 3

The values of the correction factor for flux attenuation and multiple scattering in a polythene sample with a height of 3.0 cm, an inner diameter of 0.62 cm and an outer diameter of 0.95 cm calculated according to Cranberg et al. [45] with a scattering angle of 30°.

E (MeV)	2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
k	1.17	1.16	1.15	1.14	1.14	1.13	1.13	1.12	1.12	1.12	1.12

Table 5

The values of the optical model parameters used in the present work.

Element	U (MeV)	W (MeV)	r_{0U} (fm)	r_{0W} (fm)
^{27}Al	48.42	7.85	1.191	1.194
^{46}Ti	50.48	8.85	1.197	1.201
^{47}Ti	50.52	8.88	1.197	1.202
^{48}Ti	50.56	8.92	1.197	1.202
^{49}Ti	50.59	8.95	1.198	1.203
^{50}Ti	50.62	8.97	1.198	1.203
^{51}V	50.64	9.00	1.198	1.203
^{50}Cr	50.62	8.97	1.198	1.203
^{52}Cr	50.66	9.03	1.199	1.204
^{54}Cr	50.70	9.07	1.199	1.205
^{55}Mn	50.71	9.10	1.200	1.205
^{54}Fe	50.70	9.07	1.199	1.205
^{56}Fe	50.72	9.12	1.200	1.205
^{59}Co	50.73	9.18	1.201	1.207
^{58}Ni	50.73	9.16	1.200	1.206
^{60}Ni	50.73	9.19	1.201	1.207
^{62}Ni	50.72	9.22	1.202	1.208
^{63}Cu	50.71	9.24	1.202	1.208
^{65}Cu	50.69	9.26	1.203	1.209
^{69}Ga	50.63	9.30	1.204	1.211
^{71}Ga	50.59	9.31	1.204	1.211
^{89}Y	49.97	9.31	1.210	1.219
^{93}Nb	49.81	9.28	1.211	1.220
^{115}In	48.76	8.99	1.218	1.229
^{141}Pr	47.42	8.41	1.225	1.239
^{206}Pb	44.25	6.24	1.245	1.265
^{207}Pb	44.20	6.20	1.245	1.266
^{208}Pb	44.16	6.17	1.245	1.266
^{209}Bi	44.12	6.13	1.246	1.267

Table 6

Measured inelastic scattering cross sections for Al given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

[illegible]

Table 7

Measured inelastic scattering cross sections for Ti given in mb. The cross sections are given for the natural element. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.00	2.26	2.51	2.75	3.00	3.25	3.52	3.78	4.02	4.26	4.50
0.889 (^{46}Ti)	2^+	591 $\pm$ 89	564 $\pm$ 85	500 $\pm$ 75	473 $\pm$ 71	532 $\pm$ 80	565 $\pm$ 85					
0.983 (^{48}Ti)	2^+											
1.247 (^{47}Ti)	$9/2^-$											
1.382 (^{49}Ti)	$3/2^-$							17 $\pm$ 4	20 $\pm$ 5	20 $\pm$ 5	20 $\pm$ 5	21 $\pm$ 5
1.442 (^{47}Ti)	$11/2^-$											
1.542 (^{49}Ti)	$11/2^-$											
1.549 (^{47}Ti)	$3/2^-$											
1.55 (^{50}Ti)	2^+									62 $\pm$ 9	60 $\pm$ 9	61 $\pm$ 9
1.585 (^{49}Ti)	$3/2^-$											
1.622 (^{49}Ti)	$9/2^-$											
1.723 (^{49}Ti)	$1/2^-$											
1.762 (^{49}Ti)	$5/2^-$			11 $\pm$ 3	14 $\pm$ 4							
1.793 (^{47}Ti)	$1/2^-$											
1.821 (^{47}Ti)	$3/2^+$											
2.010 (^{46}Ti)	4^+					20 $\pm$ 5						
2.161 (^{47}Ti)	$3/2^-$											
2.256 (^{47}Ti)	$3/2^-$											
2.262 (^{49}Ti)	$7/2^-$			84 $\pm$ 17								
2.295 (^{48}Ti)	4^+											
2.360 (^{47}Ti)	$1/2^+$											
2.414 (^{47}Ti)	$1/2^-$											
2.421 (^{48}Ti)	2^+											
2.470 (^{49}Ti)	$1/2^+$					264 $\pm$ 79						
2.504 (^{49}Ti)	$1/2^+$											
2.506 (^{49}Ti)	$15/2^-$											
2.516 (^{49}Ti)	$7/2^-$											

Table 8

Measured inelastic scattering cross sections for V given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.320	$5/2^-$	397 ± 60	362 ± 54	311 ± 47	290 ± 44	289 ± 43	237 ± 36	233 ± 35	194 ± 29	164 ± 25	115 ± 17	110 ± 17
0.930	$3/2^-$	108 ± 16	128 ± 19	107 ± 16	113 ± 17	122 ± 18	108 ± 16	98 ± 15	89 ± 13	63 ± 9	61 ± 9	52 ± 8
1.609	$11/2^-$				187 ± 28	195 ± 29	215 ± 32	216 ± 32	175 ± 26	148 ± 22	111 ± 17	104 ± 16
1.813	$9/2^-$				244 ± 49	211 ± 32	200 ± 30	201 ± 30	189 ± 28	168 ± 25	121 ± 18	95 ± 14
2.41	$3/2^-$						50 ± 13	34 ± 7	37 ± 6	33 ± 5	34 ± 5	47 ± 7
2.545	$1/2^+$							23 ± 6	11 ± 3	15 ± 4	14 ± 4	23 ± 5
2.675	$3/2^+$							60 ± 15	47 ± 7	62 ± 9	53 ± 8	55 ± 8
2.699	$15/2^-$											
2.790	$1/2^-$								21 ± 5	16 ± 4	10 ± 3	10 ± 3

Table 9

Measured inelastic scattering cross sections for Cr given in mb. The cross sections are given for the natural element. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.783 (^{50}Cr)	2^+	66 ± 10	72 ± 11	67 ± 10	65 ± 10	62 ± 9						
0.835 (^{54}Cr)	2^+											
1.434 (^{52}Cr)	2^+			518 ± 78	555 ± 83	489 ± 73	449 ± 67	451 ± 68	412 ± 62	354 ± 53	286 ± 43	299 ± 45

Table 10

Measured inelastic scattering cross sections for Mn given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

[illegible]

Measured inelastic scattering cross sections for Fe given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

[illegible]

Measured inelastic scattering cross sections for Co given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
1.100	$3/2^-$	100 ± 15	87 ± 13	88 ± 13	75 ± 11	83 ± 12	57 ± 9	65 ± 10				
1.190	$7/2^-$		274 ± 41	226 ± 34	209 ± 31	184 ± 28	167 ± 25	140 ± 21				
1.291	$3/2^-$		96 ± 14	83 ± 12	77 ± 12	66 ± 10	49 ± 7	43 ± 6				
1.434	$1/2^-$											
1.463	$7/2^-$		461 ± 138	343 ± 51	274 ± 41	251 ± 38	217 ± 33	204 ± 31				
1.482	$5/2^-$											
1.744	$7/2^-$				141 ± 21	115 ± 17	96 ± 14	94 ± 14				

Measured inelastic scattering cross sections for Ni given in mb. The cross sections for the two last groups of levels are given for the natural element while the others are given for 100 per cent abundances. I^π denotes the spin and parity used in the MHF and HF calculations.

[illegible]

Table 14

Measured inelastic scattering cross sections for Cu given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.670 (^{63}Cu)	$1/2^-$	126 ± 19	130 ± 20	117 ± 18	109 ± 16	88 ± 13	61 ± 9	57 ± 9	53 ± 11	29 ± 6	33 ± 7	31 ± 6
0.771 (^{65}Cu)	$1/2^-$	159 ± 24	167 ± 25	147 ± 22	145 ± 22	132 ± 20	91 ± 14	97 ± 15	60 ± 12	51 ± 10	42 ± 8	33 ± 7
0.962 (^{63}Cu)	$5/2^-$	285 ± 43	224 ± 34	216 ± 32	194 ± 29	180 ± 27	152 ± 23	133 ± 20	121 ± 18	83 ± 12	77 ± 12	68 ± 10
1.115 (^{65}Cu)	$5/2^-$	342 ± 51	263 ± 39	224 ± 34	184 ± 28	187 ± 28	145 ± 22	161 ± 24	124 ± 19	127 ± 19	99 ± 15	104 ± 16

Table 15

Measured inelastic scattering cross sections for Ga given in mb. I^π denotes the spin and parity used in the MHF and HF calculations. The cross sections are given for the natural element.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.00	2.26	2.51	2.75	3.00	3.25	3.52	3.78	4.02	4.26	4.50
0.319 (^{69}Ga)	$1/2^-$	90 $\pm$ 14	91 $\pm$ 18	47 $\pm$ 9	47 $\pm$ 9	53 $\pm$ 11	42 $\pm$ 8					
0.390 (^{71}Ga)	$1/2^-$											
0.487 (^{71}Ga)	$5/2^-$											
0.512 (^{71}Ga)	$3/2^-$											
0.574 (^{69}Ga)	$5/2^-$	268 $\pm$ 40	218 $\pm$ 33	183 $\pm$ 27	151 $\pm$ 23	135 $\pm$ 20	114 $\pm$ 17					
0.872 (^{69}Ga)	$3/2^-$											
0.911 (^{71}Ga)	$3/2^-$											
0.965 (^{71}Ga)	$5/2^-$											
1.027 (^{69}Ga)	$1/2^-$	226 $\pm$ 34	217 $\pm$ 33	169 $\pm$ 25	154 $\pm$ 23	121 $\pm$ 18	111 $\pm$ 17					
1.108 (^{69}Ga)	$3/2^-$											
1.108 (^{71}Ga)	$7/2^-$											
1.334 (^{69}Ga)	$7/2^-$											
1.395 (^{71}Ga)	$7/2^-$	212 $\pm$ 32	153 $\pm$ 23	140 $\pm$ 21	122 $\pm$ 18	115 $\pm$ 17	106 $\pm$ 16					
1.476 (^{71}Ga)	$7/2^-$											
1.488 (^{69}Ga)	$5/2^-$											
1.494 (^{71}Ga)	$9/2^+$											
1.499 (^{71}Ga)	$5/2^-$	101 $\pm$ 20		93 $\pm$ 14	75 $\pm$ 11	81 $\pm$ 12	72 $\pm$ 11					
1.524 (^{69}Ga)	$3/2^-$											
				183 $\pm$ 27	171 $\pm$ 26	144 $\pm$ 22	134 $\pm$ 20					

Table 16

Measured inelastic scattering cross sections for Y given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

[illegible]

Table 17

Measured inelastic scattering cross sections for Nb given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

[illegible]

Table 18

Measured inelastic scattering cross sections for In given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.336	$1/2^-$	24 ± 6	16 ± 4	18 ± 5	18 ± 5							
0.597	$3/2^-$	28 ± 7	21 ± 5	20 ± 5	22 ± 6							

Table 19

Measured inelastic scattering cross sections for Pr given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.145	$7/2^+$	332 ± 66	251 ± 50	135 ± 27								
1.118	$11/2^-$	272 ± 41	246 ± 37	209 ± 31	161 ± 24			67 ± 10	54 ± 8	49 ± 7		
1.128	$3/2^+$											
1.292	$5/2^+$	206 ± 31	240 ± 36	190 ± 29	153 ± 23			62 ± 9	52 ± 8	48 ± 7		
1.299	$1/2^+$											
1.435	$3/2^+$											
1.450	$3/2^+$											
1.455	$7/2^+$	503 ± 75	501 ± 75	460 ± 69	380 ± 57			187 ± 28	146 ± 22	111 ± 17		
1.493	$5/2^+$											
1.520	$1/2^+$											
1.578	$5/2^+$											
1.607	$3/2^+$		295 ± 44	330 ± 50	257 ± 39			112 ± 17	80 ± 12	70 ± 11		
1.649	$1/2^+$											
1.783	$7/2^+$											
1.809	$1/2^+$				325 ± 49			181 ± 27	125 ± 19	104 ± 16		
1.841	$5/2^+$											
1.856	$3/2^+$											

Table 20

Measured inelastic scattering cross sections for Pb given in mb. The figures within brackets are obtained with a Pb-scatterer and the others with a Pb_r -scatterer. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.570 (^{207}Pb)	$5/2^-$	701 ± 105 (598 $\pm$ 90)	830 ± 125 (805 $\pm$ 121)	783 ± 117 (766 $\pm$ 115)	804 ± 121 (839 $\pm$ 126)	712 ± 107 (752 $\pm$ 113)	797 ± 120 (805 $\pm$ 121)	520 ± 104 (678 $\pm$ 102)	492 ± 123 (462 $\pm$ 69)	554 ± 139 (499 $\pm$ 75)		325 ± 81 (199 $\pm$ 30)
0.803 (^{206}Pb)	2^+	411 ± 62 (429 $\pm$ 64)	417 ± 63 (426 $\pm$ 64)	410 ± 62 (443 $\pm$ 66)	444 ± 67 (494 $\pm$ 74)	409 ± 61 (412 $\pm$ 62)	444 ± 67 (447 $\pm$ 67)	347 ± 52 (349 $\pm$ 52)	295 ± 44 (297 $\pm$ 45)	229 ± 34 (231 $\pm$ 35)		147 ± 22 (148 $\pm$ 22)
0.894 (^{207}Pb)	$3/2^-$	(343 ± 51)	(405 ± 61)	(414 ± 62)	(451 ± 68)	(399 ± 60)	(392 ± 59)	(382 ± 57)	(294 ± 44)	(279 ± 42)		(192 ± 29)
1.165 (^{206}Pb)	0^+	120 ± 24	73 ± 11 (100 $\pm$ 20)	67 ± 10 (94 $\pm$ 19)	75 ± 11 (105 $\pm$ 21)	67 ± 10 (75 $\pm$ 15)	80 ± 12 (91 $\pm$ 23)	45 ± 9 (52 $\pm$ 16)	50 ± 10 (44 $\pm$ 13)	46 ± 12 (69 $\pm$ 21)		22 ± 6 (32 $\pm$ 10)
1.341 (^{206}Pb)	3^+		243 ± 36 (293 $\pm$ 44)	210 ± 32 (233 $\pm$ 35)	225 ± 34 (274 $\pm$ 41)	251 ± 38 (273 $\pm$ 41)	222 ± 33 (246 $\pm$ 37)	229 ± 34 (263 $\pm$ 39)	213 ± 32 (236 $\pm$ 35)	204 ± 31 (218 $\pm$ 33)		141 ± 21 (146 $\pm$ 22)
1.460 (^{206}Pb)	2^+			188 ± 28 (218 $\pm$ 33)	189 ± 28 (207 $\pm$ 31)	159 ± 24 (213 $\pm$ 32)	177 ± 26 (236 $\pm$ 35)	179 ± 27 (205 $\pm$ 31)	166 ± 25 (183 $\pm$ 27)	131 ± 20 (179 $\pm$ 27)		93 ± 14 (121 $\pm$ 18)
2.615 (^{208}Pb)	3^-								(936 ± 140)	(888 ± 133)		(674 ± 101)

Table 21

Measured inelastic scattering cross sections for Bi given in mb. I^π denotes the spin and parity used in the MHF and HF calculations.

Excitation energy (MeV)	I^π	Incident neutron energy (MeV)										
		2.02	2.27	2.50	2.77	3.01	3.29	3.52	3.78	4.02	4.26	4.50
0.897	$7/2^-$	236 ± 35	305 ± 46	357 ± 54	381 ± 57	381 ± 57	339 ± 51	317 ± 48	308 ± 46	197 ± 30	164 ± 25	136 ± 20
1.609	$13/2^+$			295 ± 17	236 ± 14	250 ± 15	237 ± 14	231 ± 14	258 ± 15	155 ± 9	122 ± 7	97 ± 6
2.492	$3/2^+$											
2.563	$9/2^+$											
2.582	$7/2^+$							367 ± 22	449 ± 26	367 ± 22	344 ± 20	269 ± 16
2.599	$11/2^+$											
2.601	$13/2^+$											
2.616	$5/2^+$											
2.741	$15/2^+$											
2.822	$5/2^-$								129 ± 8	102 ± 6	96 ± 6	86 ± 5
2.827	$7/2^-$											

Table 22

Values of the nuclear temperature parameter T and the level density parameter a' obtained from least square fits to the continuous neutron inelastic spectra of In and Ta. The last column shows the values of the parameter a' calculated according to eq (27).

Element	Primary neutron energy (MeV)	T (MeV)	Experimentally determined value of a' (MeV^{-1})	Calculated value of a' (MeV^{-1})
In	4.02	0.37 ± 0.03	32.5	36.0
	4.26	0.41 ± 0.03	28.1	31.4
	4.50	0.45 ± 0.03	25.0	27.8
Ta	3.78	0.44 ± 0.03	22.0	25.4
	4.02	0.47 ± 0.03	20.6	23.8
	4.26	0.47 ± 0.03	21.2	24.7
	4.50	0.49 ± 0.03	20.3	24.0

Table 23

The neutron inelastic scattering cross sections determined in the present work have been compared with the results published in the references given in this table. The techniques used in the measurements are also given as well as the energy ranges covered. The time-of-flight method (T o f) refers to measurements, in which the scattered neutrons have been detected.

Element	Method	Neutron energy range (MeV)	Year	Reference
Al	T o f	1.4 - 4.0	1962	(31)
	γ -ray study with Ge(Li) detector	0.8 - 13	1971	(19)
V	γ -ray study with NaI detector	1.0 - 3.1	1968	(18)
	T o f	1.0 - 3.8	1968	(34)
Cr	γ -ray study with NaI detector	1 - 3	1964	(100)
Mn	γ -ray study with NaI detector	1.0 - 3.1	1968	(18)
Fe	T o f	2.0 - 5.0	1964	(101)
	T o f	1 - 4	1965	(32)
Co	T o f	1.8 - 4.0	1973	(102)
⁵⁸ Ni, ⁶⁰ Ni	γ -ray study with NaI detector	1 - 4	1964	(100)
	T o f	1.3 - 4.0	1966	(33)
Ni	γ -ray study with Ge(Li) detector	threshold -1.8	1971	(103)
Y	γ -ray study with NaI detector	0.8 - 3.4	1963	(86)
	T o f	1.6 - 3.8	1969	(35)
Nb	γ -ray study with Ge(Li) detector	threshold -1.8	1971	(103)
	T o f	1.0 - 5.0	1971	(38)
	T o f	threshold -4.0	1973	(104)
Pr	T o f	0.23 - 2.58	1969	(105)
	T o f	1.5 - 3.5	1972	(106)
Pb	T o f	2.0 - 5.0	1967	(98)
Bi	T o f	2.0 - 5.0	1967	(98)
	T o f	1.5 - 3.5	1972	(106)

Table 24

Inelastic neutron cross sections for ^{56}Fe at a primary neutron energy of 3.0 MeV calculated with the Hauser-Feshbach formalism with 3 different values of the parameter W .

Case 1			Case 2			Case 3		
Generalized parameters			W increased with 2 per cent			W increased with 10 per cent		
U	=	50.72 MeV	U	=	50.72 MeV	U	=	50.72 MeV
W	=	9.12 MeV	W	=	9.30 MeV	W	=	10.03 MeV
r_{0U}	=	1.200 fm	r_{0U}	=	1.200 fm	r_{0U}	=	1.200 fm
r_{0W}	=	1.205 fm	r_{0W}	=	1.205 fm	r_{0W}	=	1.205 fm
a	=	0.66 fm	a	=	0.66 fm	a	=	0.66 fm
Ur_{0U}^2	=	73.01 MeV fm ²						

Level excitation energy (MeV)	I^π	Case 1 σ_{inel} (barns)	Case 2 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 2	Case 3 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 3
0	0^+	0.383	0.385	0.995	0.394	0.972
0.845	2^+	0.889	0.892	0.997	0.905	0.982
2.085	4^+	0.162	0.162	1.000	0.164	0.988
2.658	2^+	0.244	0.244	1.000	0.243	1.004
2.94	0^+	0.0225	0.0224	1.004	0.0216	1.042

Table 25

Inelastic neutron cross sections for ^{56}Fe at a primary neutron energy of 3.0 MeV calculated with the Hauser-Feshbach formalism with 3 different values of the parameter r_{0W} .

Case 1			Case 2			Case 3		
Generalized parameters			r_{0W} increased with 2 per cent			r_{0W} increased with 5 per cent		
U	=	50.72 MeV	U	=	50.72 MeV	U	=	50.72 MeV
W	=	9.12 MeV	W	=	9.12 MeV	W	=	9.12 MeV
r_{0U}	=	1.200 fm	r_{0U}	=	1.200 fm	r_{0U}	=	1.200 fm
r_{0W}	=	1.205 fm	r_{0W}	=	1.230 fm	r_{0W}	=	1.266 fm
a	=	0.66 fm	a	=	0.66 fm	a	=	0.66 fm
Ur_{0U}^2	=	73.01 MeV fm ²						

Level excitation energy (MeV)	I^π	Case 1 σ_{inel} (barns)	Case 2 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 2	Case 3 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 3
0	0^+	0.383	0.384	0.997	0.385	0.995
0.845	2^+	0.889	0.886	1.003	0.885	1.005
2.085	4^+	0.162	0.162	1.000	0.164	0.988
2.658	2^+	0.244	0.239	1.021	0.231	1.056
2.94	0^+	0.0225	0.0216	1.042	0.0201	1.119

Table 26

Inelastic neutron cross sections for ^{56}Fe at a primary neutron energy of 3.0 MeV calculated with the Hauser-Feshbach formalism with 3 different values of the parameter U.

Case 1			Case 2			Case 3		
Generalized parameters			U increased with 2 per cent			U increased with 5 per cent		
U	=	50.72 MeV	U	=	51.73 MeV	U	=	53.26 MeV
W	=	9.12 MeV	W	=	9.12 MeV	W	=	9.12 MeV
r_{0U}	=	1.200 fm	r_{0U}	=	1.200 fm	r_{0U}	=	1.200 fm
r_{0W}	=	1.205 fm	r_{0W}	=	1.205 fm	r_{0W}	=	1.205 fm
a	=	0.66 fm	a	=	0.66 fm	a	=	0.66 fm
Ur_{0U}^2	=	73.01 MeV fm ²	Ur_{0U}^2	=	74.47 MeV fm ²	Ur_{0U}^2	=	76.67 MeV fm ²

Level ex-citation energy (MeV)	I^π	Case 1 σ_{inel} (barns)	Case 2 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 2	Case 3 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 3
0.0	0^+	0.383	0.379	1.011	0.377	1.016
0.845	2^+	0.889	0.879	1.011	0.867	1.025
2.085	4^+	0.162	0.163	0.994	0.164	0.988
2.658	2^+	0.244	0.237	1.030	0.221	1.104
2.94	0^+	0.0225	0.0215	1.047	0.0186	1.210

Table 27

Inelastic neutron cross sections for ^{56}Fe at a primary neutron energy of 3.0 MeV calculated with the Hauser-Feshbach formalism with 3 different values of the parameter r_{0U} .

Case 1			Case 2			Case 3		
Generalized parameters			r_{0U} increased with 2 per cent			r_{0U} increased with 5 per cent		
U	=	50.72 MeV	U	=	50.72 MeV	U	=	50.72 MeV
W	=	9.12 MeV	W	=	9.12 MeV	W	=	9.12 MeV
r_{0U}	=	1.200 fm	r_{0U}	=	1.224 fm	r_{0U}	=	1.260 fm
r_{0W}	=	1.205 fm	r_{0W}	=	1.205 fm	r_{0W}	=	1.205 fm
a	=	0.66 fm	a	=	0.66 fm	a	=	0.66 fm
Ur_{0U}^2	=	73.01 MeV fm ²	Ur_{0U}^2	=	75.96 MeV fm ²	Ur_{0U}^2	=	80.50 MeV fm ²

Level ex-citation energy (MeV)	I^π	Case 1 σ_{inel} (barns)	Case 2 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 2	Case 3 σ_{inel} (barns)	Ratio between the cross sections obtained in Case 1 and Case 3
0.0	0^+	0.383	0.379	1.011	0.385	0.995
0.845	2^+	0.889	0.883	1.007	0.887	1.002
2.085	4^+	0.162	0.172	0.942	0.194	0.835
2.658	2^+	0.244	0.234	1.043	0.211	1.156
2.94	0^+	0.0225	0.0206	1.092	0.0151	1.490

Table 28

Inelastic neutron cross sections for ^{56}Fe at a primary energy of 3.0 MeV calculated with the Hauser-Feshbach formalism with 3 different values of the parameter a .

Case 1	Case 2	Case 3
Generalized parameters	a increased with 2 per cent	a increased with 5 per cent
U = 50.72 MeV	U = 50.72 MeV	U = 50.72 MeV
W = 9.12 MeV	W = 9.12 MeV	W = 9.12 MeV
r_{0U} = 1.200 fm	r_{0U} = 1.200 fm	r_{0U} = 1.200 fm
r_{0W} = 1.205 fm	r_{0W} = 1.205 fm	r_{0W} = 1.205 fm
a = 0.66 fm	a = 0.67 fm	a = 0.69 fm

Level ex- citation energy (MeV)	I^π	Case 1 σ_{inel} (barns)	Case 2 σ_{inel} (barns)	Ratio between the cross sec- tions obtained in Case 1 and Case 2	Case 3 σ_{inel} (barns)	Ratio between the cross sec- tions obtained in Case 1 and Case 3
0	0^+	0.383	0.384	0.997	0.387	0.990
0.845	2^+	0.889	0.895	0.993	0.908	0.979
2.085	4^+	0.162	0.166	0.976	0.175	0.926
2.658	2^+	0.244	0.246	0.992	0.249	0.980
2.94	0^+	0.0225	0.0226	0.996	0.0226	0.996

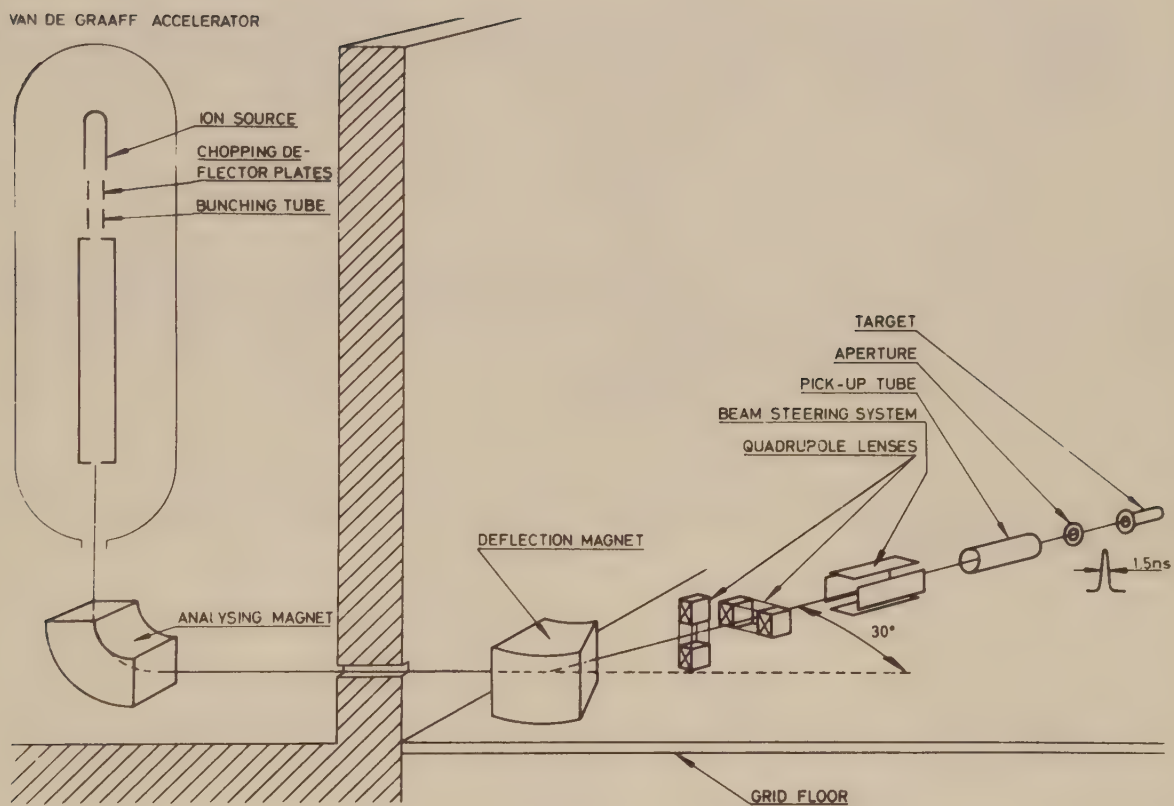


Fig 1. A schematic lay-out of the accelerator and beam alignment systems.

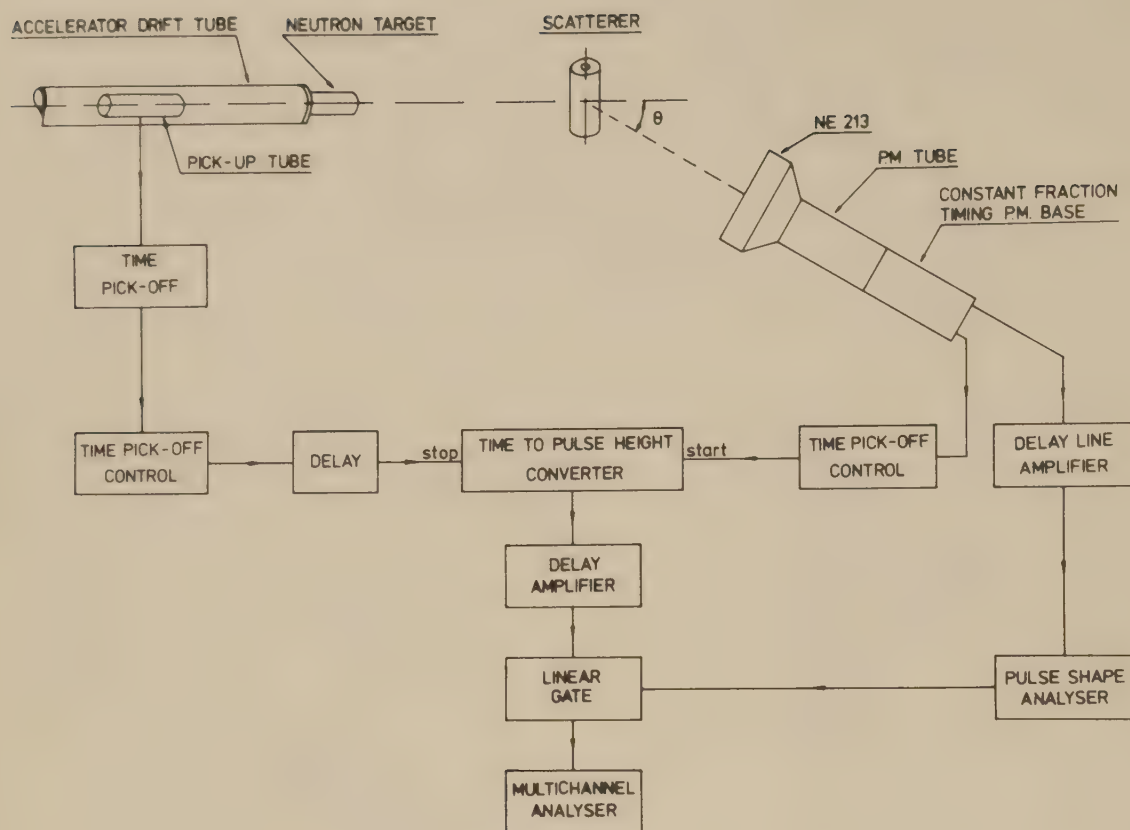


Fig 2. The block diagram of the time-of-flight electronics including (n, γ) discrimination.

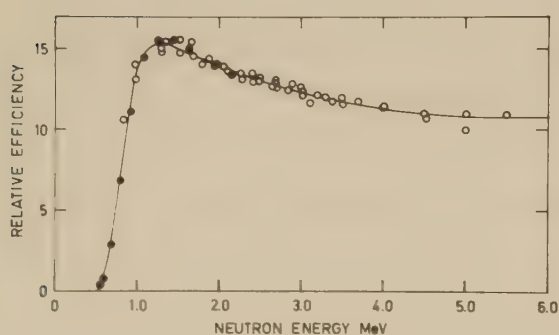


Fig 3. The relative efficiency curve of the neutron detector as measured with the $H(n, n)H$ (unfilled circles) and $T(p, n)^3He$ (filled circles) processes. The curve represents a least square fit to the experimental points.

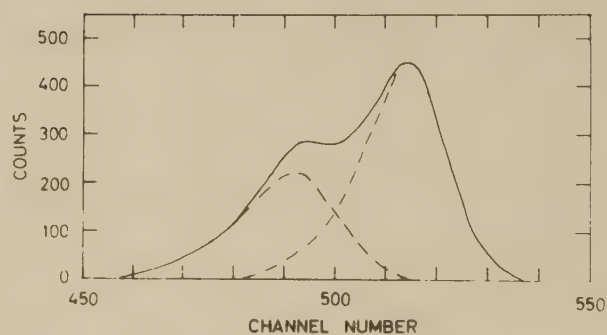


Fig 4. The analysis of two incompletely resolved peaks. The solid line represents the measured spectrum. The dotted line is the standard peak for this neutron energy normalized to a suitable height. The point dashed line represents the difference between the solid line and the dashed one.

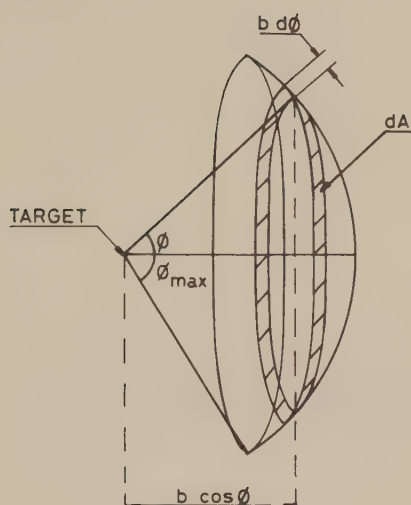


Fig 5. Notations used for the calculation of the correction factor for the anisotropic intensity distribution of the source neutrons.

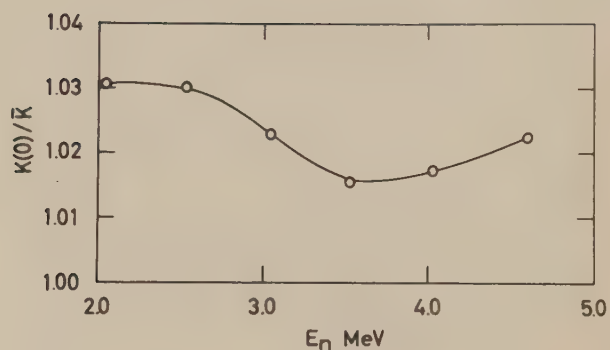


Fig 6. The variation with neutron energy of the correction factor $K(0)/\bar{K}$ for the anisotropic intensity distribution of the source neutrons.

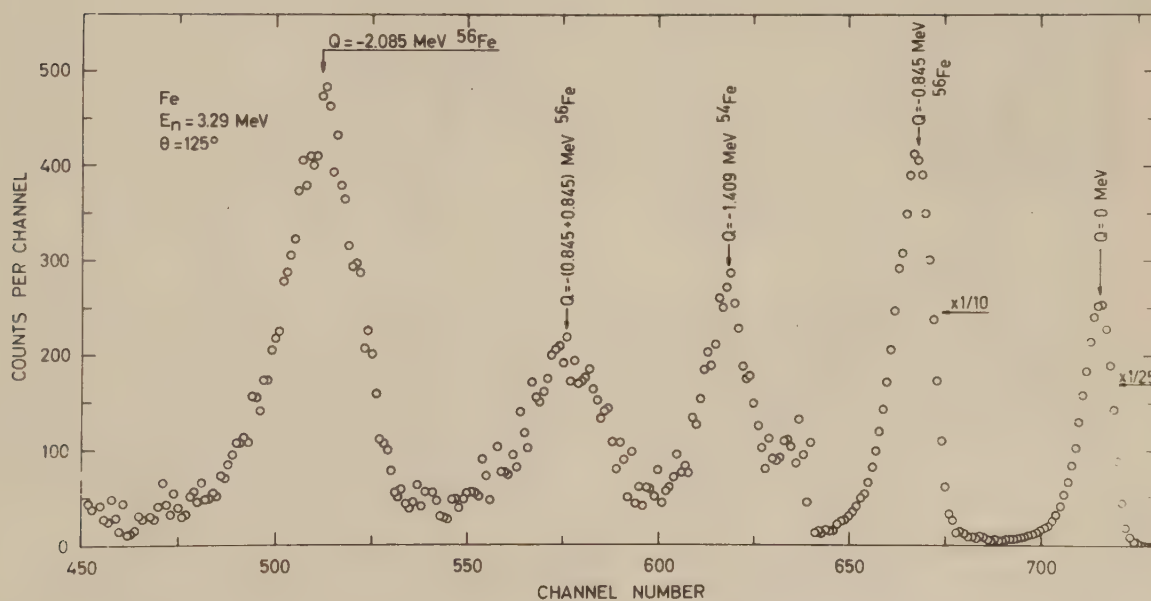


Fig 7. Neutron time-of-flight spectrum for Fe at an incident neutron energy of 3.29 MeV showing the peak at about 1.75 MeV due to double inelastic scattering from the 0.845 MeV level.

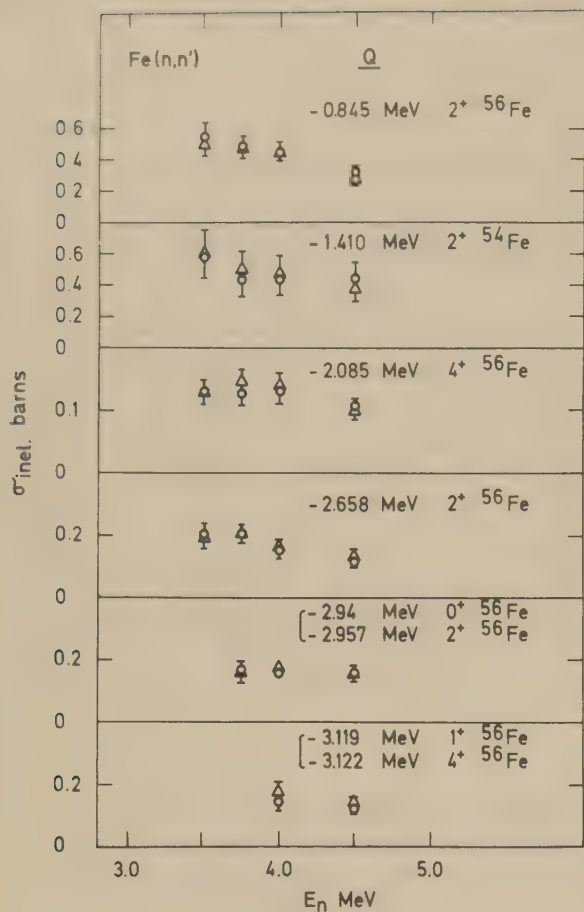


Fig 8. Excitation functions for inelastic neutron scattering from Fe obtained with a scatterer having a height of 50 mm, an outer diameter of 25 mm and an inner diameter of 9.5 mm (circles) as well as with a scatterer with the corresponding figures 30, 18 and 9.5 mm (triangles).

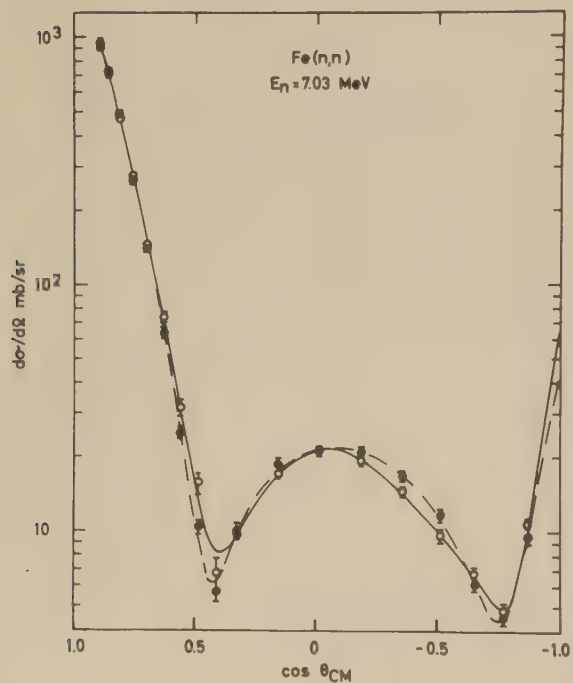


Fig 9. The corrected experimental angular distribution for Fe together with the Legendre polynomial fit to the data points obtained with a scatterer with a height of 50 mm, an outer diameter of 25 mm and an inner diameter of 9.5 mm (unfilled circles and solid line) as well as with a scatterer with the corresponding figures 30, 9.6 and 6.5 mm (filled circles and dashed line).

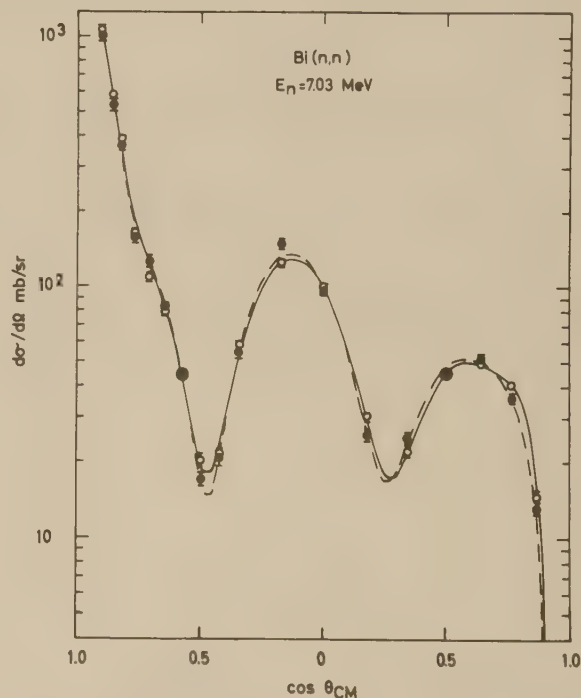


Fig 10. The corrected experimental angular distribution for Bi together with the Legendre polynomial fit to the data points. The notations are the same as in Fig 9.

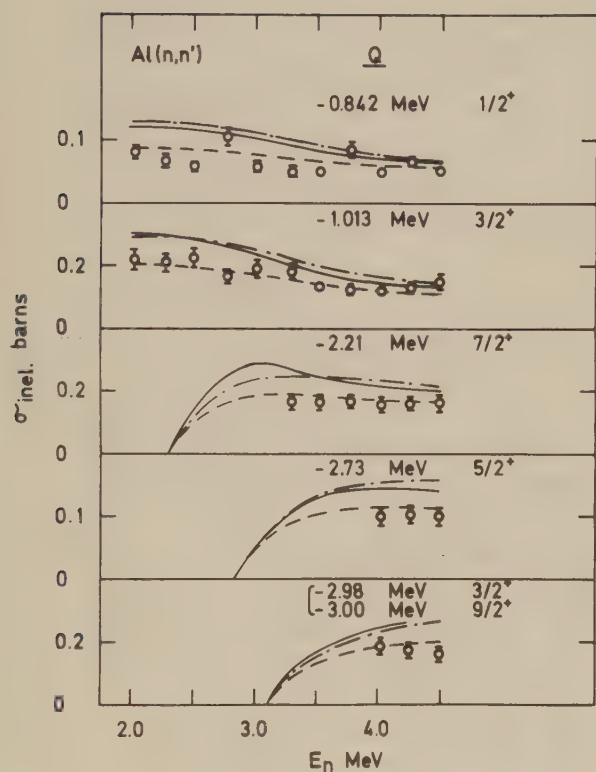


Fig 11. Excitation functions for inelastic scattering from Al. Experimental results (circles). HF calculations (solid lines). Moldauer calculations with $Q_\alpha = 0$ (dashed lines) and with $Q_\alpha = 1$ (point dashed lines).

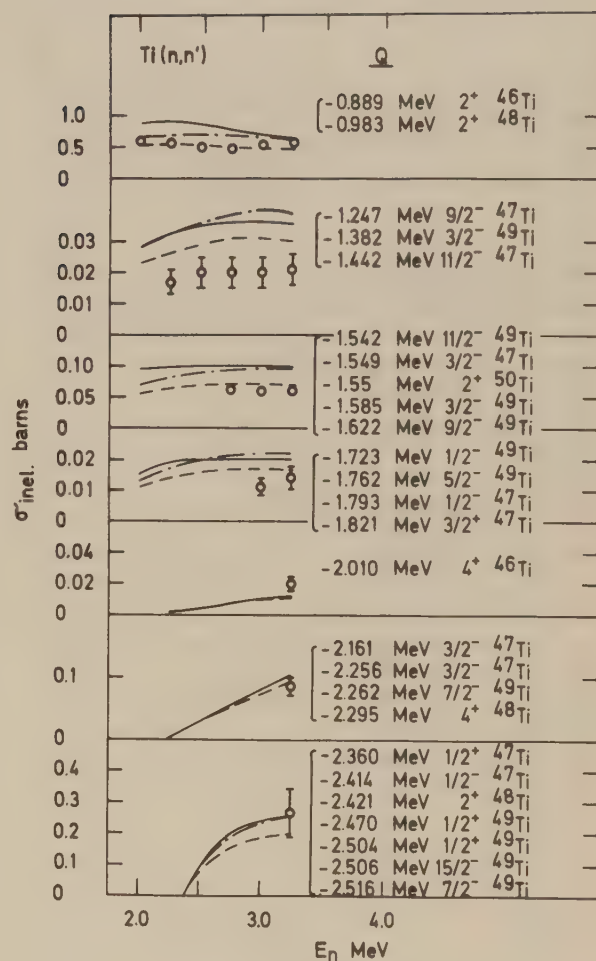


Fig 12. Excitation functions for inelastic scattering from Ti. The notations are the same as in Fig 11. The cross sections are given for the natural element.

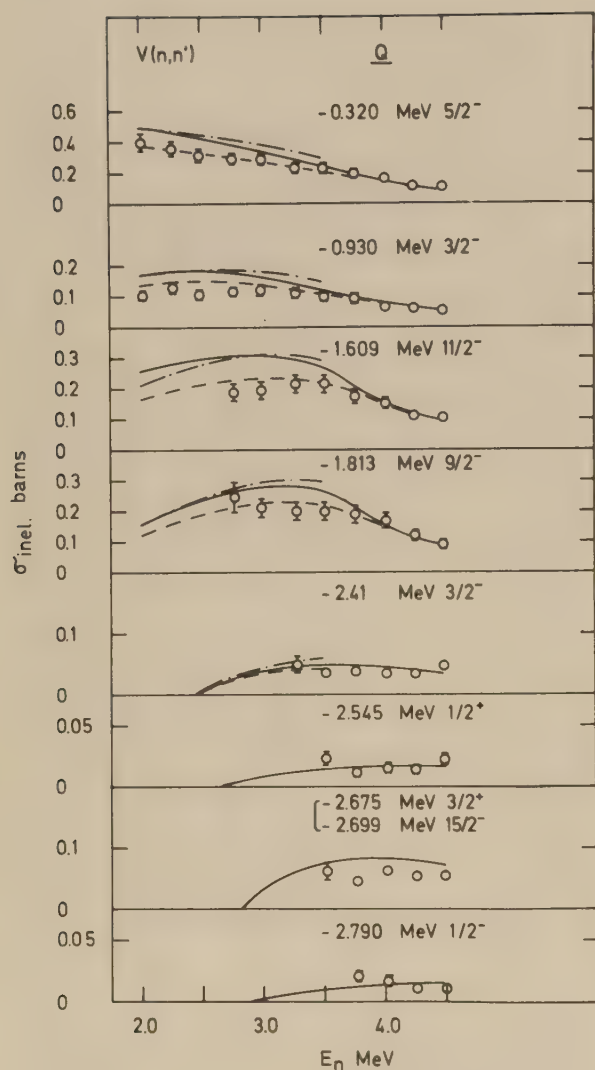


Fig 13. Excitation functions for inelastic scattering from V. The notations are the same as in Fig 11.

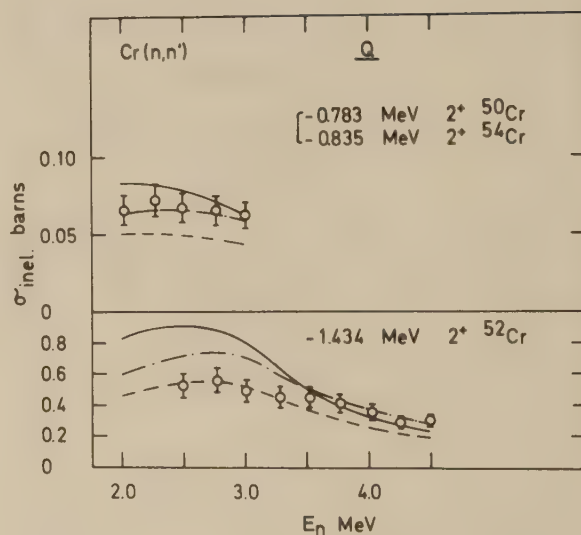


Fig 14. Excitation functions for inelastic scattering from Cr. The notations are the same as in Fig 11. The cross sections are given for the natural element.

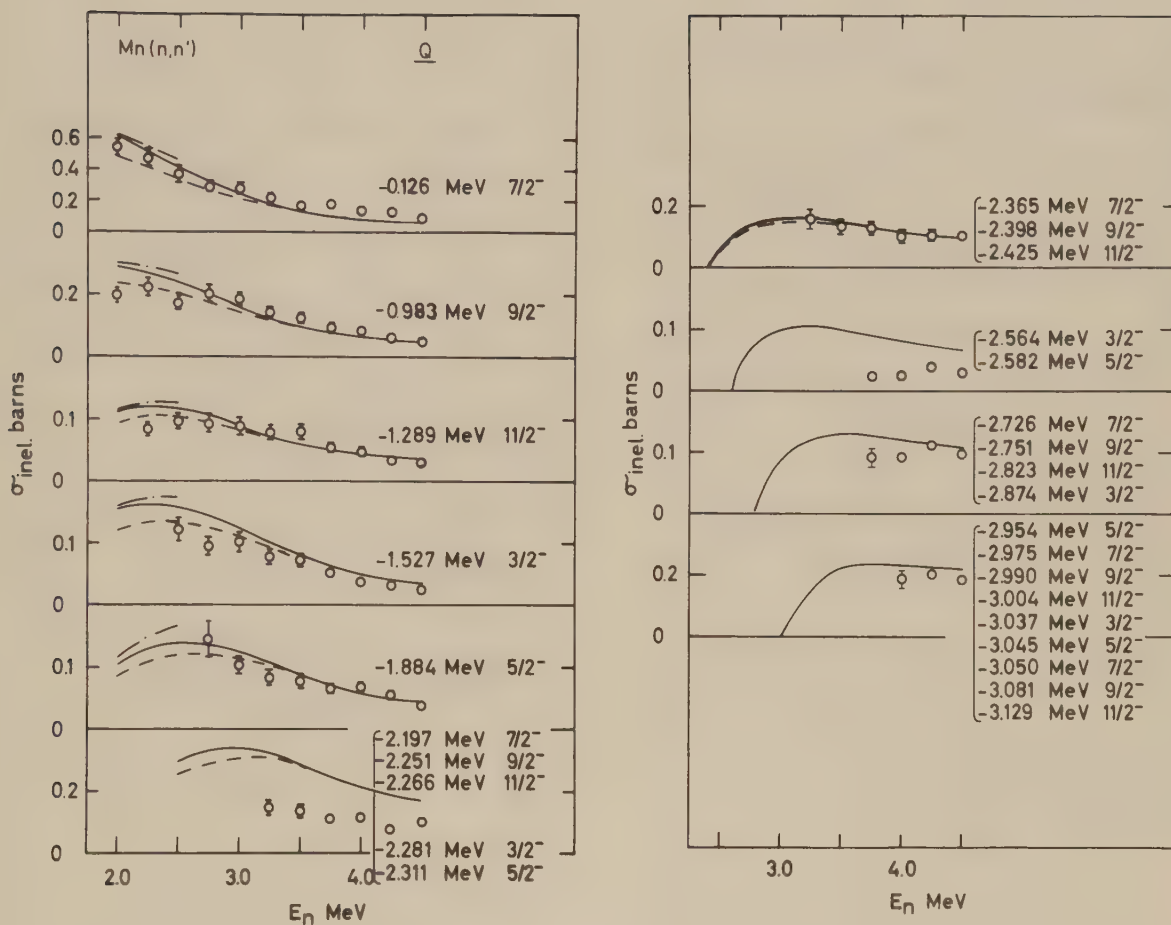


Fig 15. Excitation functions for inelastic scattering from Mn. The notations are the same as in Fig 11.

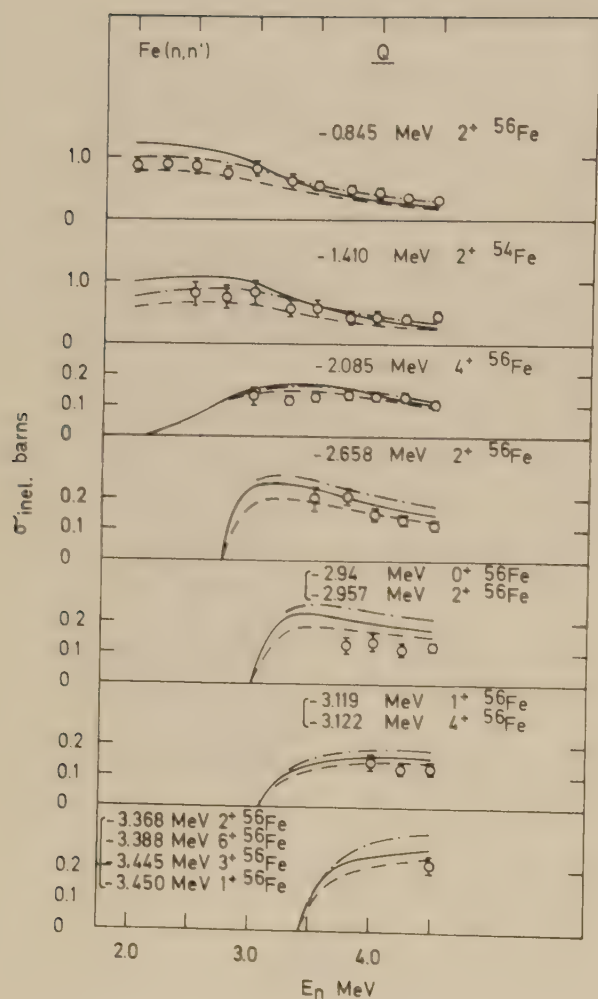


Fig 16. Excitation functions for inelastic scattering from Fe. The notations are the same as in Fig 11.

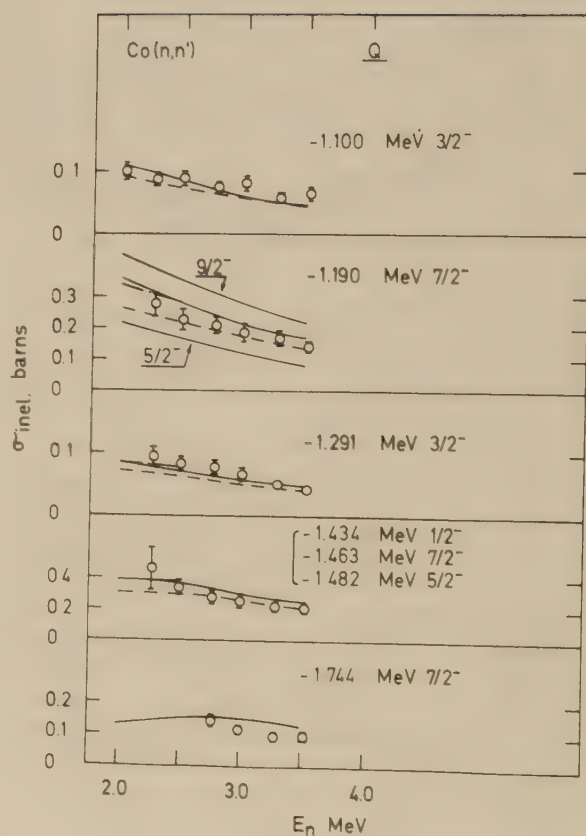


Fig 17. Excitation functions for inelastic scattering from Co. The notations are the same as in Fig 11.

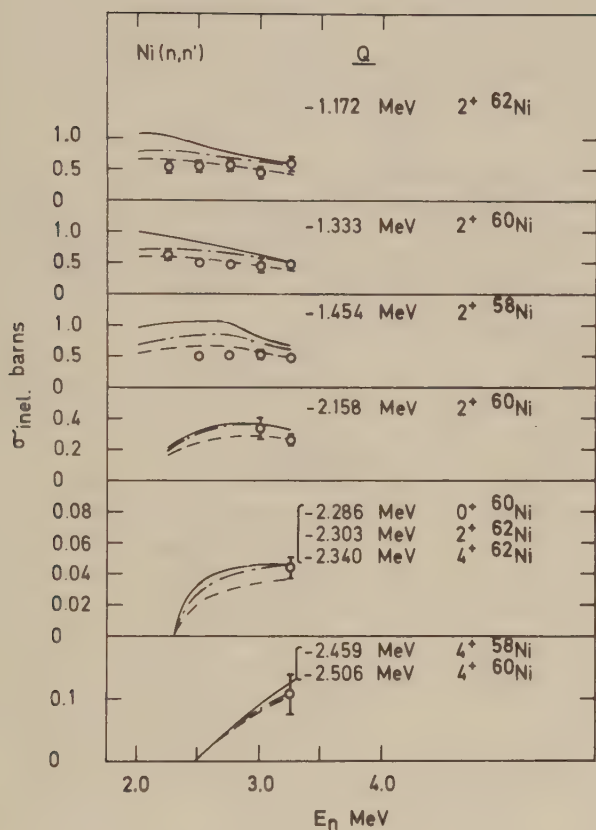


Fig 18. Excitation functions for inelastic scattering from Ni. The notations are the same as in Fig 11. The cross sections for the two last groups of levels are given for the natural element while the others are given for 100 per cent abundance of the isotopes.

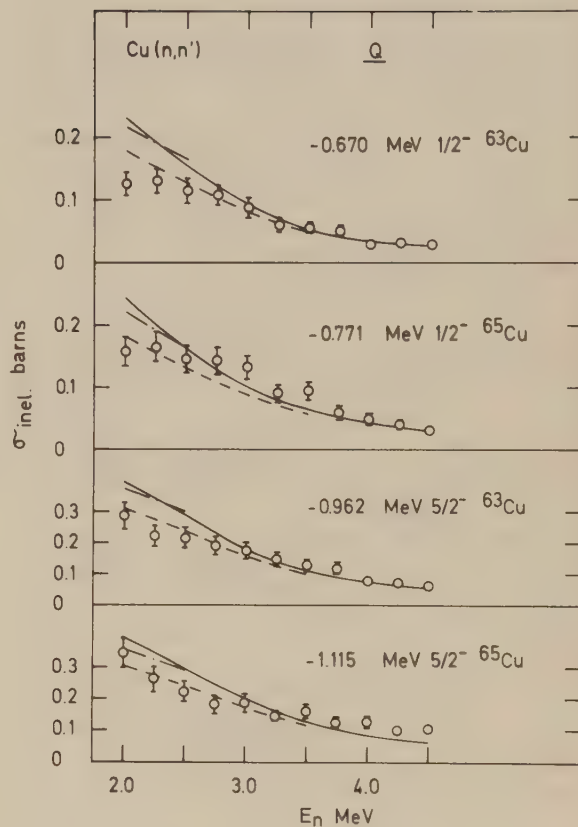


Fig 19. Excitation functions for inelastic scattering from Cu. The notations are the same as in Fig 11.

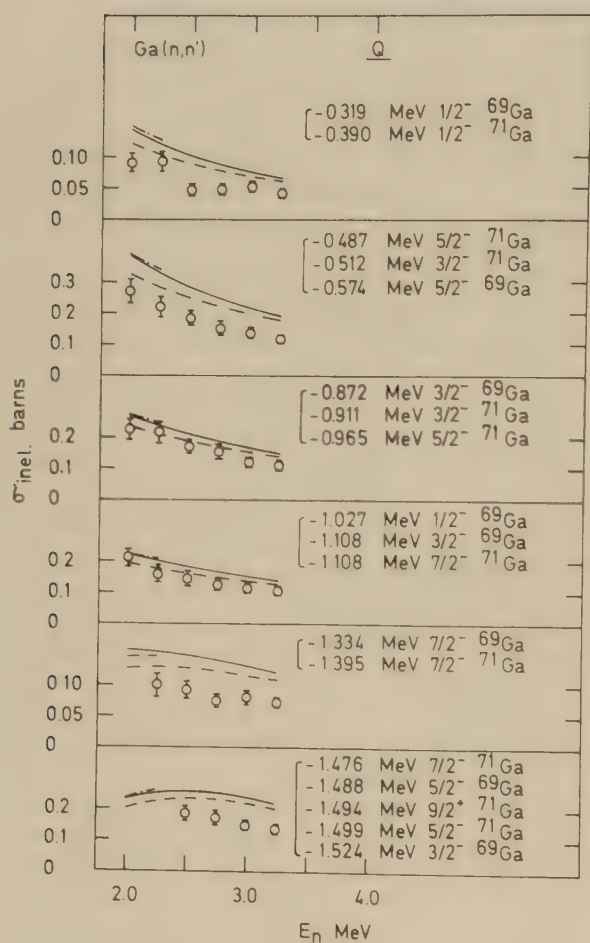


Fig 20. Excitation functions for inelastic scattering from Ga. The notations are the same as in Fig 11. The cross sections are given for the natural element.

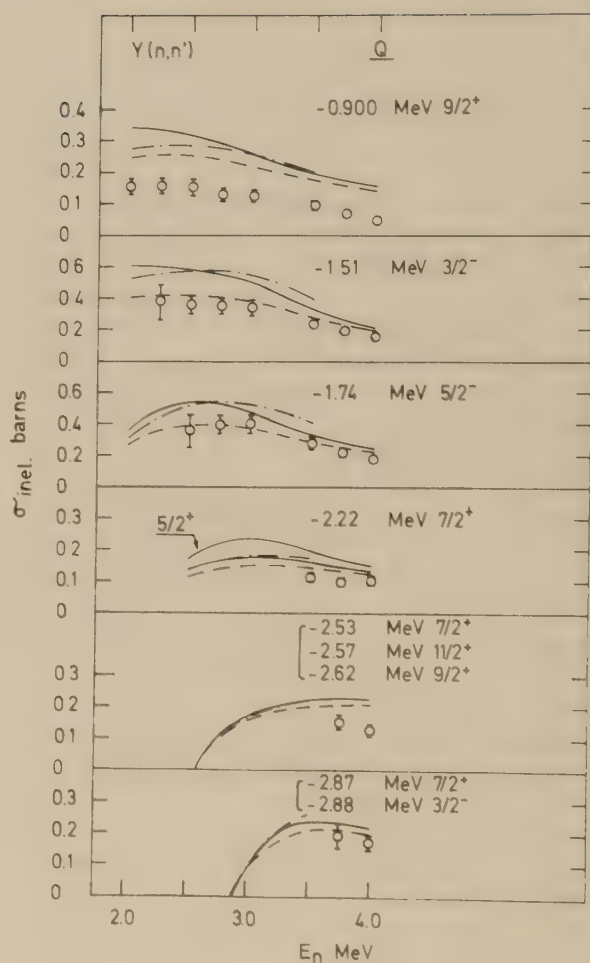


Fig 21. Excitation functions for inelastic scattering from Y. The notations are the same as in Fig 11.

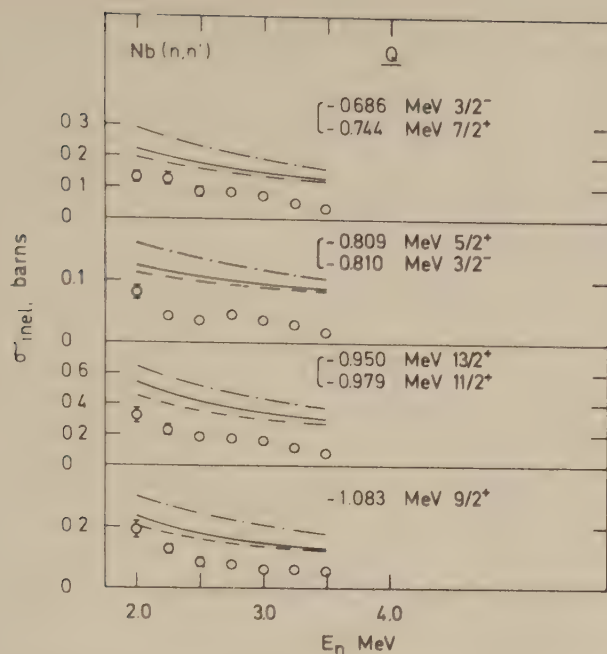


Fig 22. Excitation functions for inelastic scattering from Nb. The notations are the same as in Fig 11.

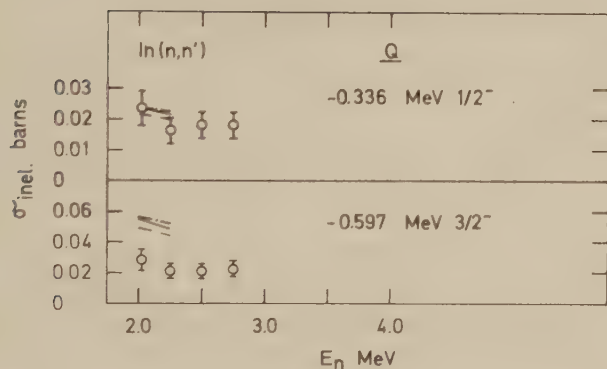


Fig 23. Excitation functions for inelastic scattering from In. The notations are the same as in Fig 11.

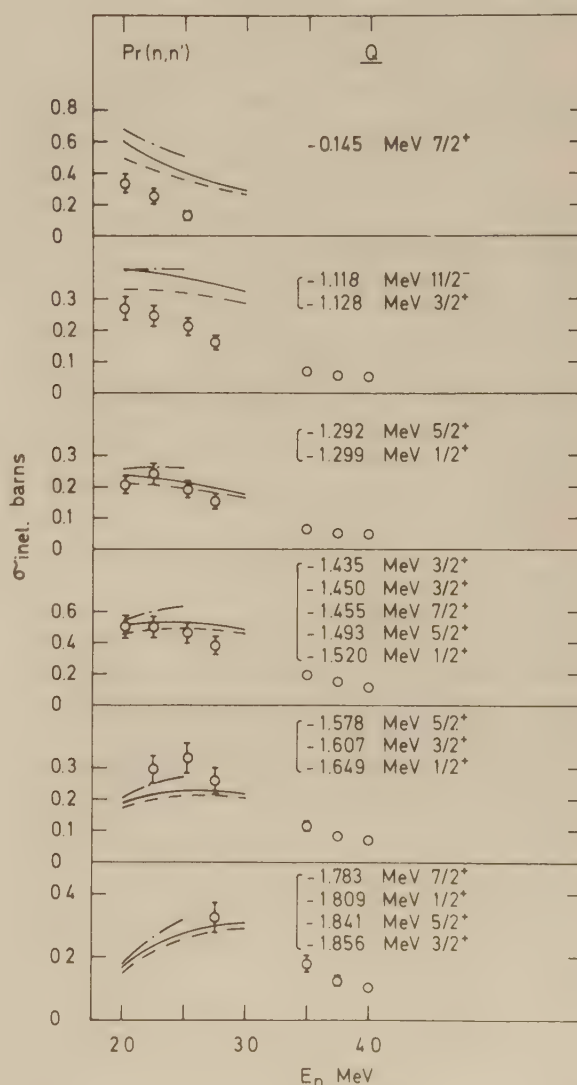
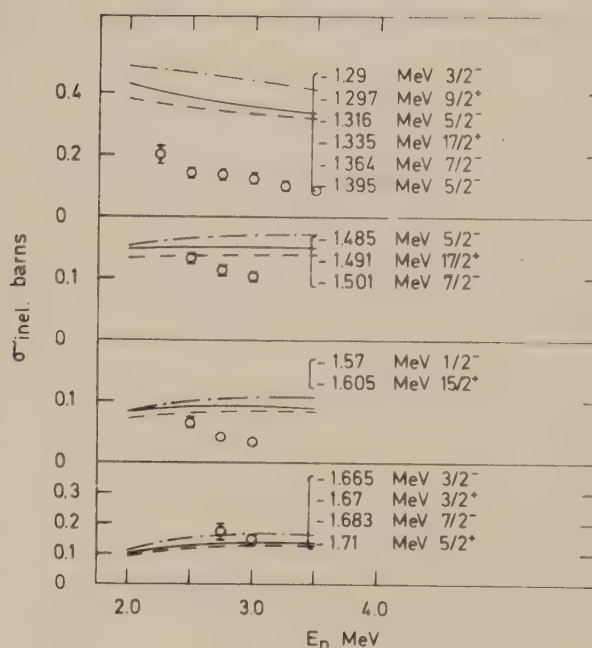


Fig 24. Excitation functions for inelastic scattering from Pr. The notations are the same as in Fig 11.

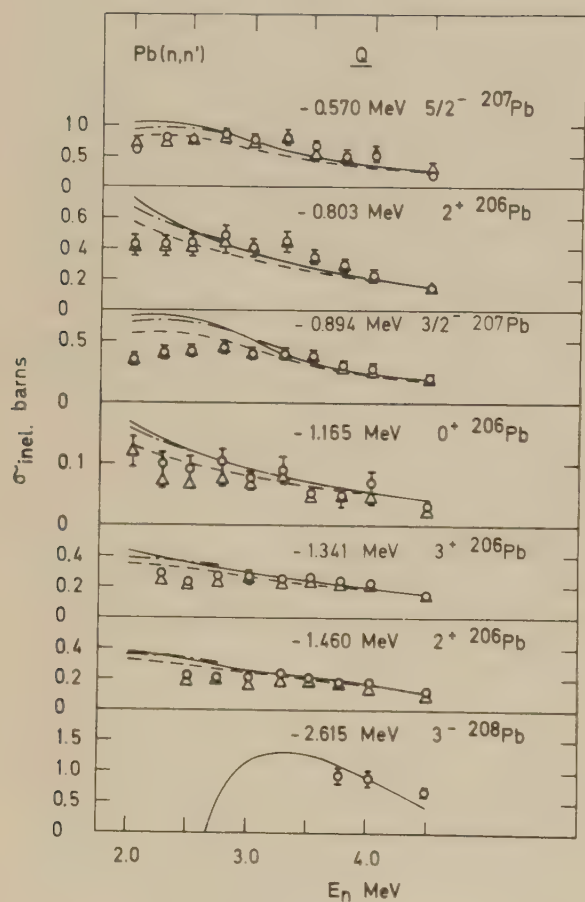


Fig 25. Excitation functions for inelastic scattering from Pb. Experimental results are obtained both with a Pb scatterer (circles) and a Pb_r scatterer (triangles). The other notations are the same as in Fig 11.

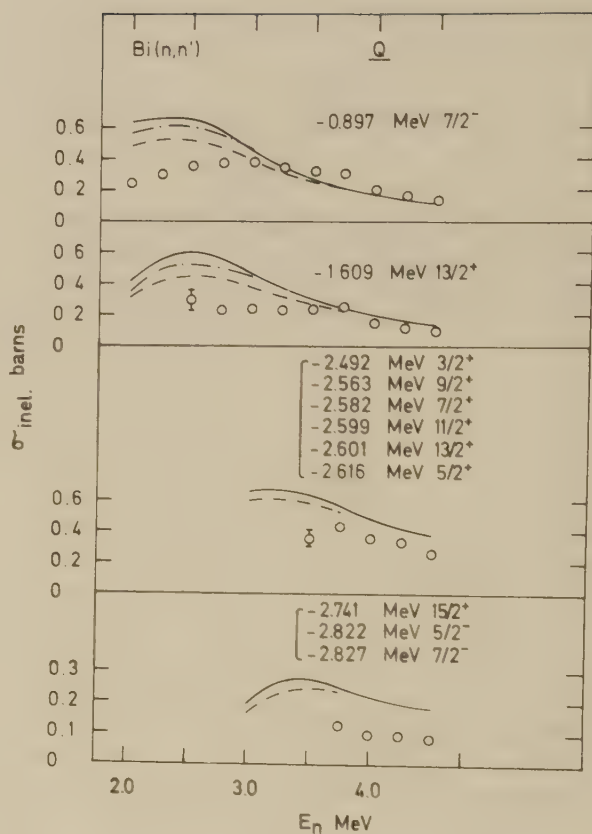


Fig 26. Excitation functions for inelastic scattering from Bi. The notations are the same as in Fig 11.

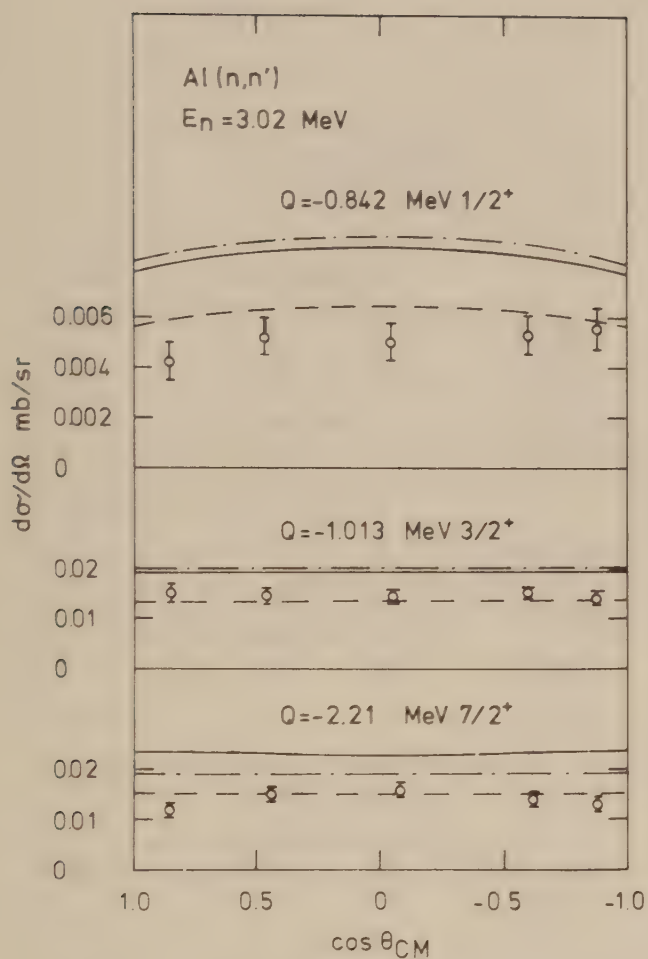


Fig 27. Angular distributions of the inelastic scattering cross sections for Al at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11.

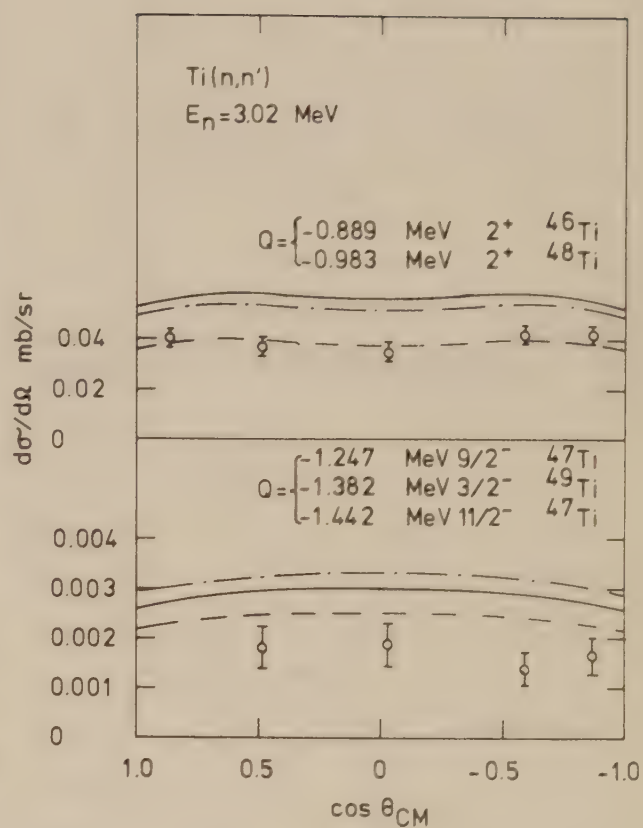


Fig 28. Angular distributions of the inelastic scattering cross sections for Ti at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11. The cross sections are given for the natural element.

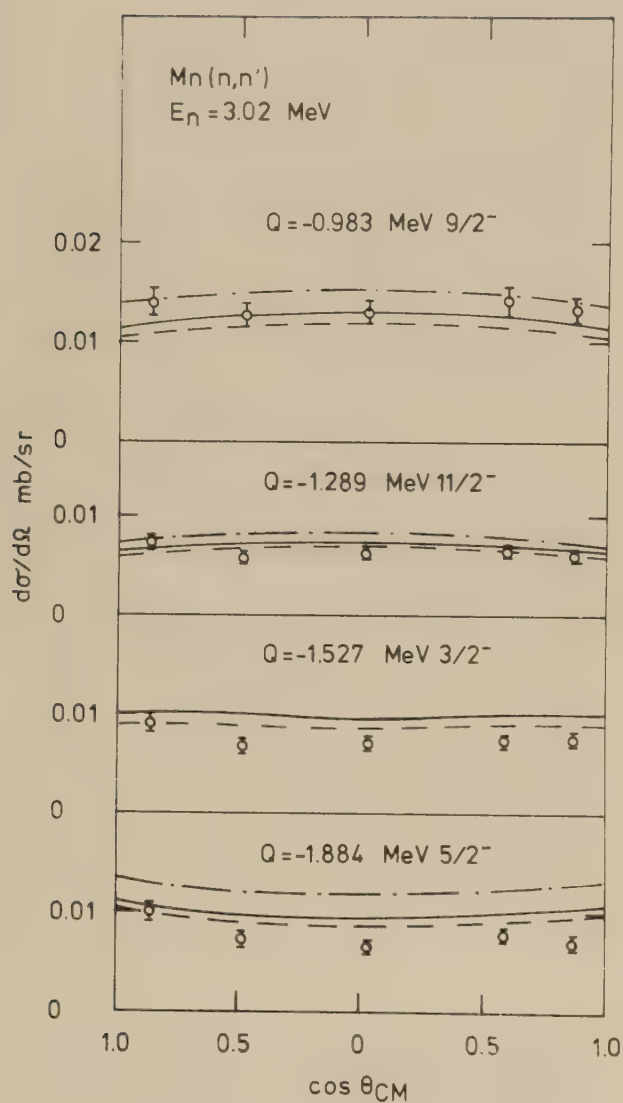


Fig 29. Angular distributions of the inelastic scattering cross sections for Mn at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11.

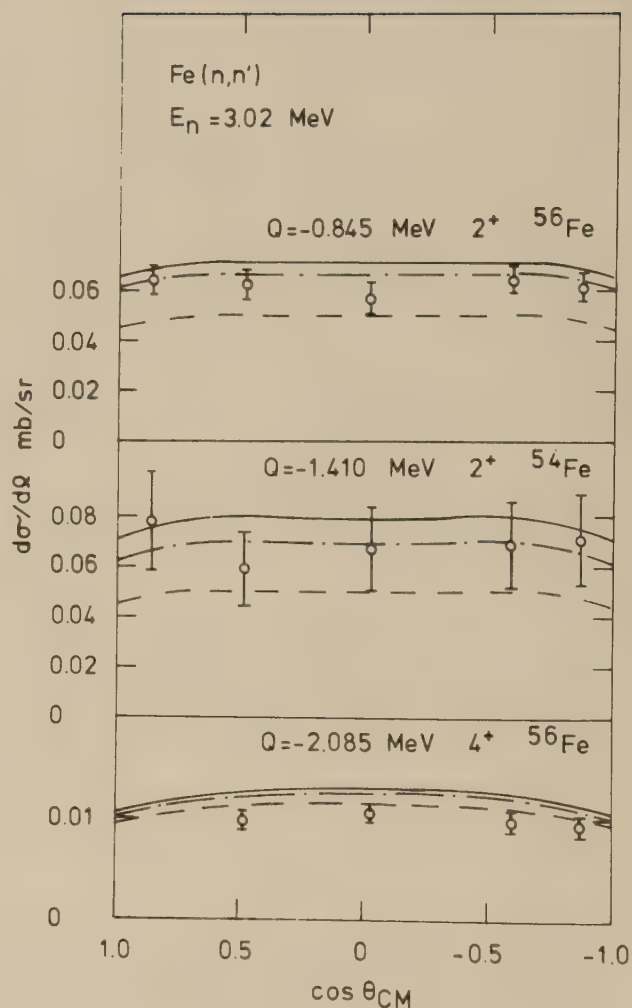


Fig 30. Angular distributions of the inelastic scattering cross sections for Fe at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11.

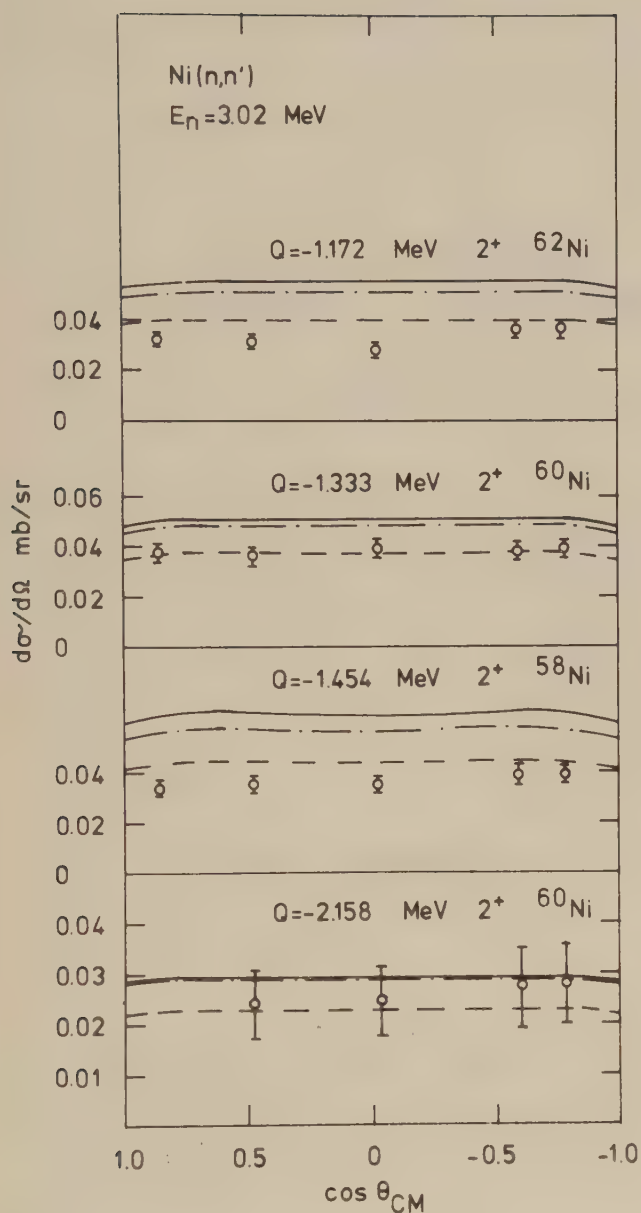


Fig 31. Angular distributions of the inelastic scattering cross sections for Ni at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11.

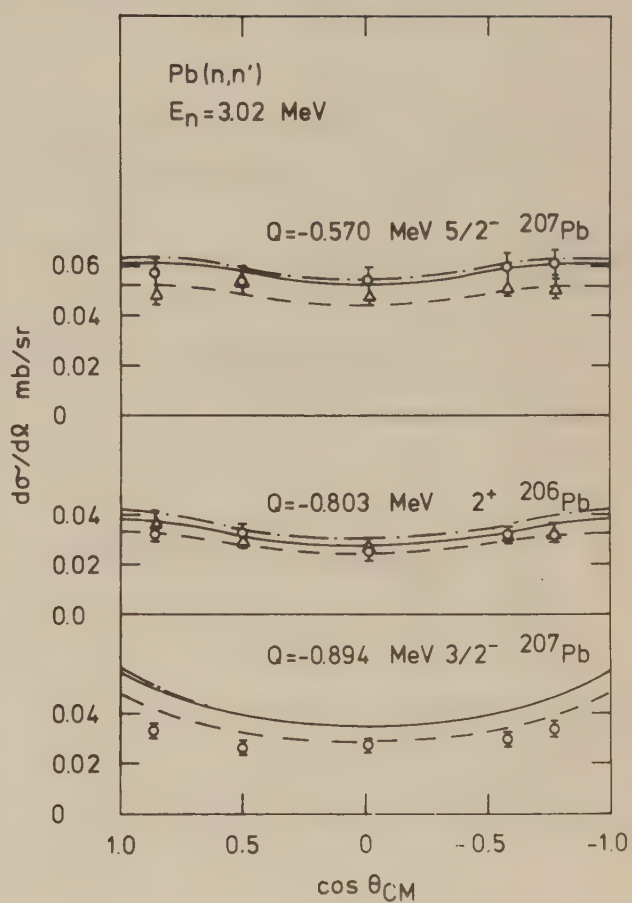


Fig 32. Angular distributions of the inelastic scattering cross sections for Pb at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11 and 25.

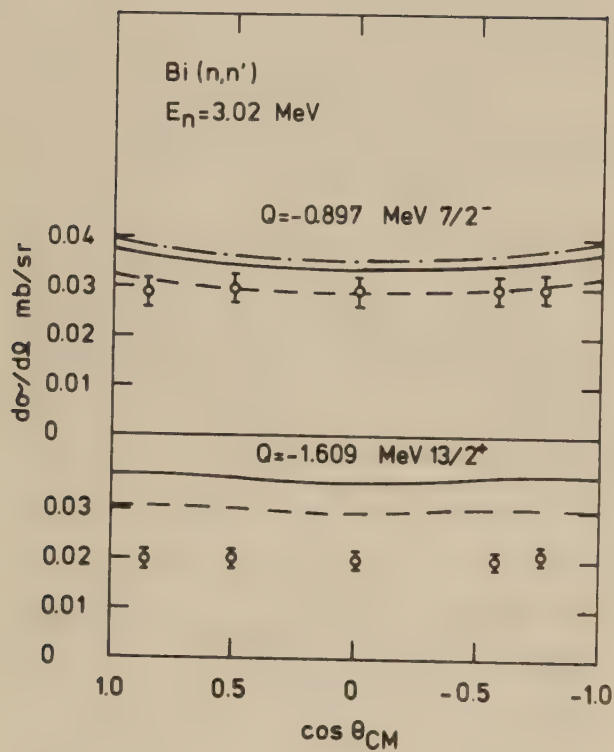


Fig 33. Angular distributions of the inelastic scattering cross sections for Bi at 3.02 MeV incident neutron energy. The notations are the same as in Fig 11.

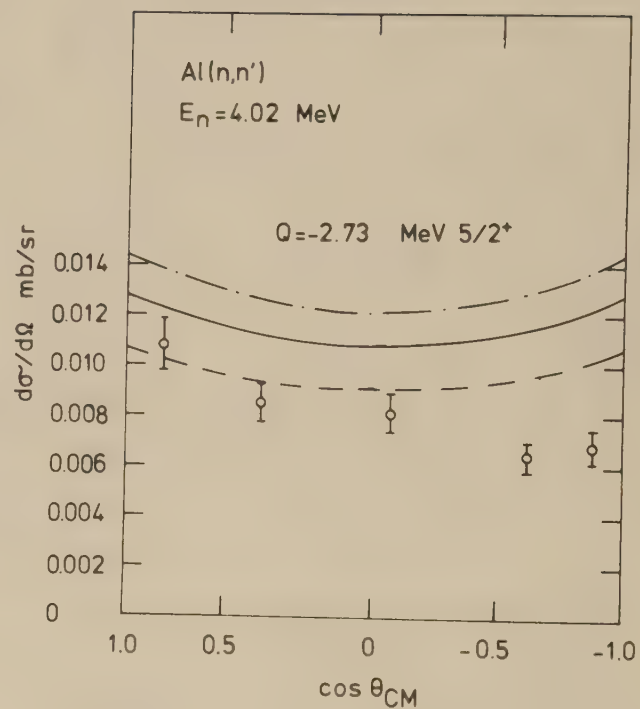


Fig 34. Angular distribution of the inelastic scattering cross sections for the 2.73 MeV level in Al at 4.02 MeV incident neutron energy. The notations are the same as in Fig 11.

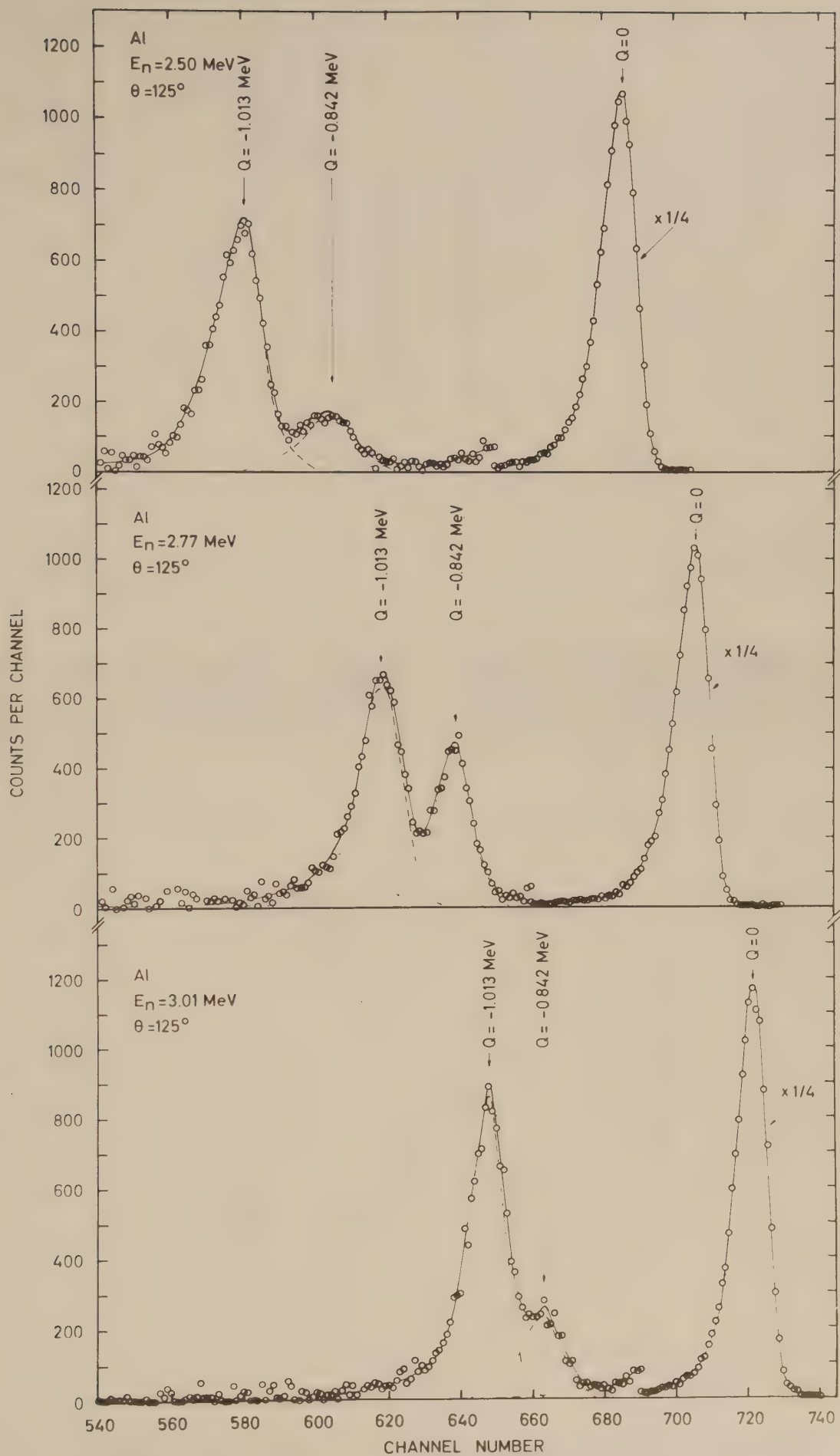


Fig 35. Time-of-flight spectra of Al at incident neutron energies of 2.50, 2.77 and 3.01 MeV.

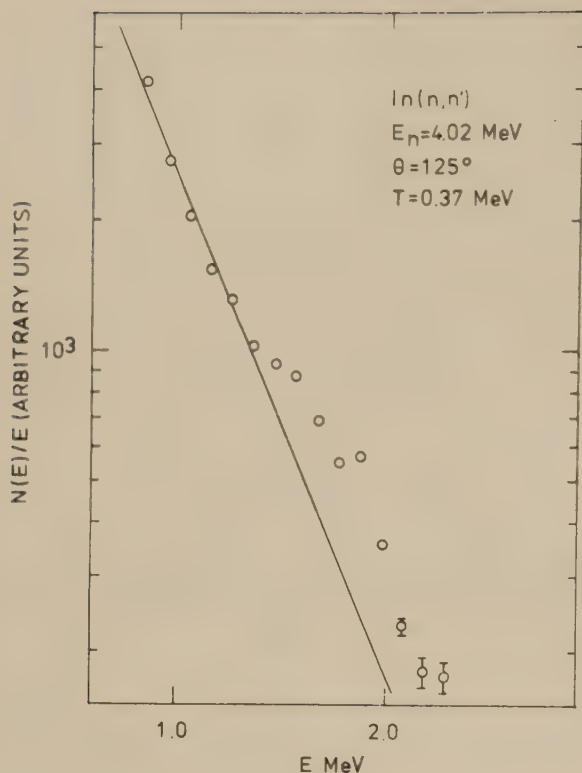


Fig 36. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 4.02 MeV neutrons from In.

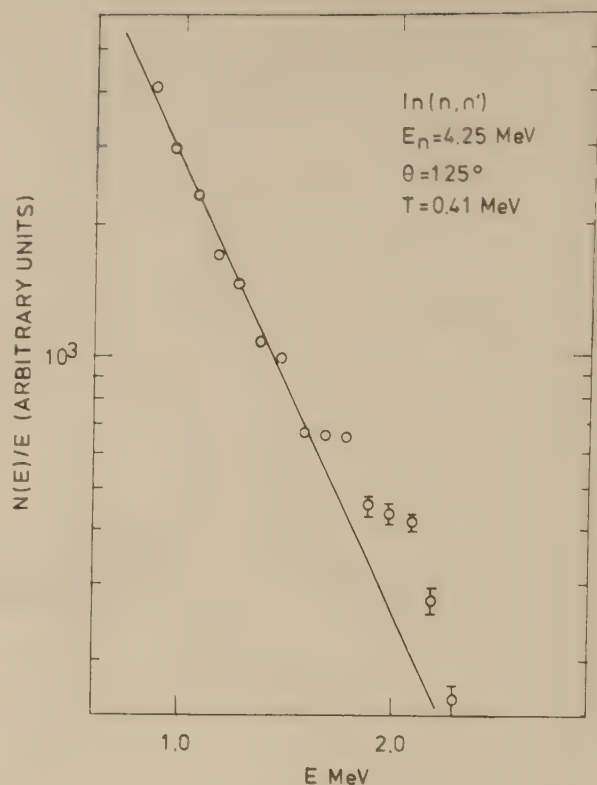


Fig 37. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 4.26 MeV neutrons from In.

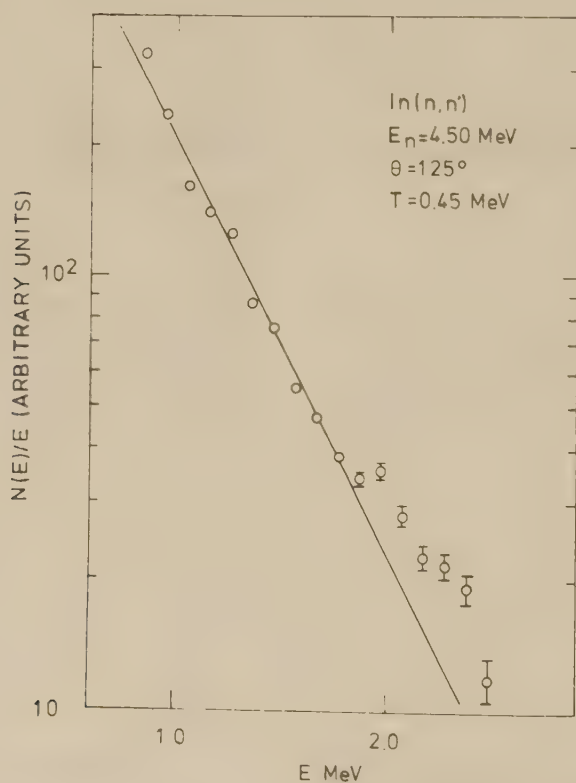


Fig 38. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 4.50 MeV neutrons from In.

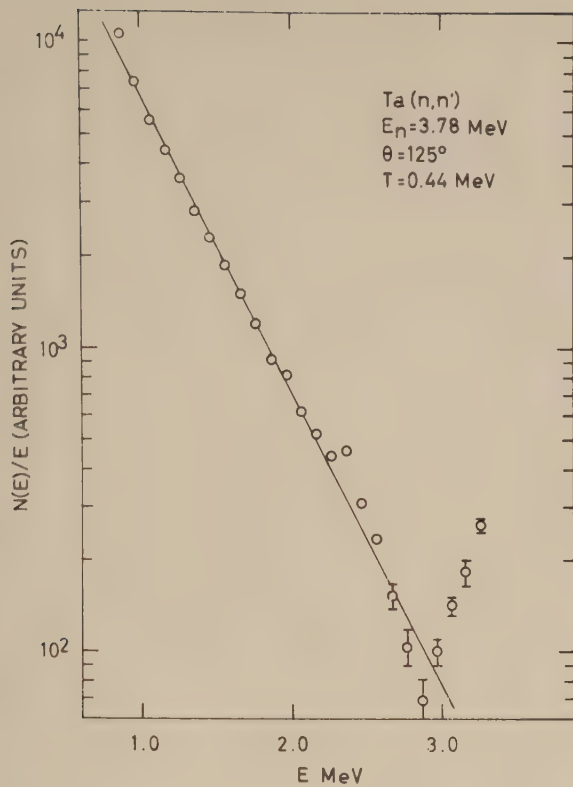


Fig 39. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 3.78 MeV neutrons from Ta.

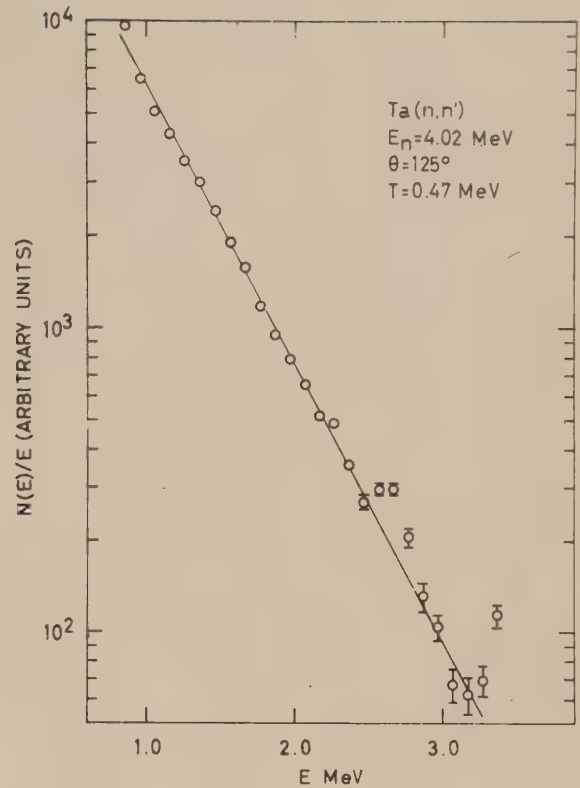


Fig 40. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 4.02 MeV neutrons from Ta.

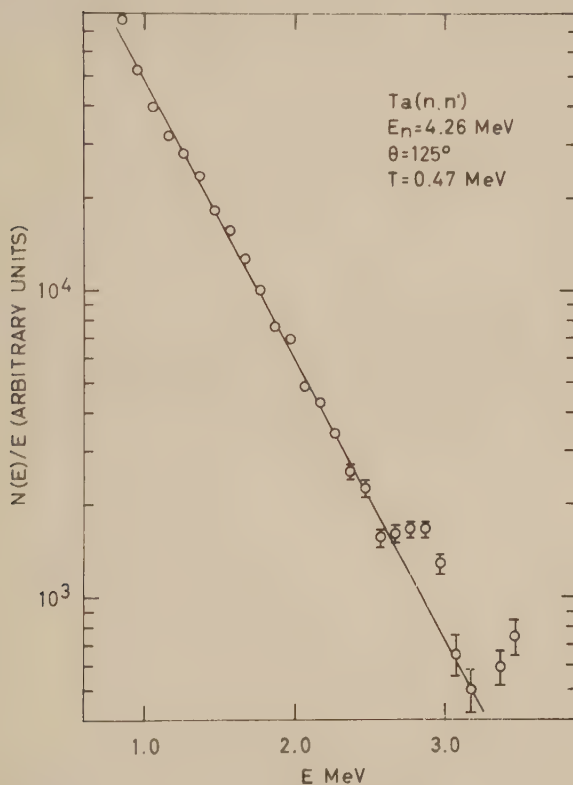


Fig 41. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 4.26 MeV neutrons from Ta.

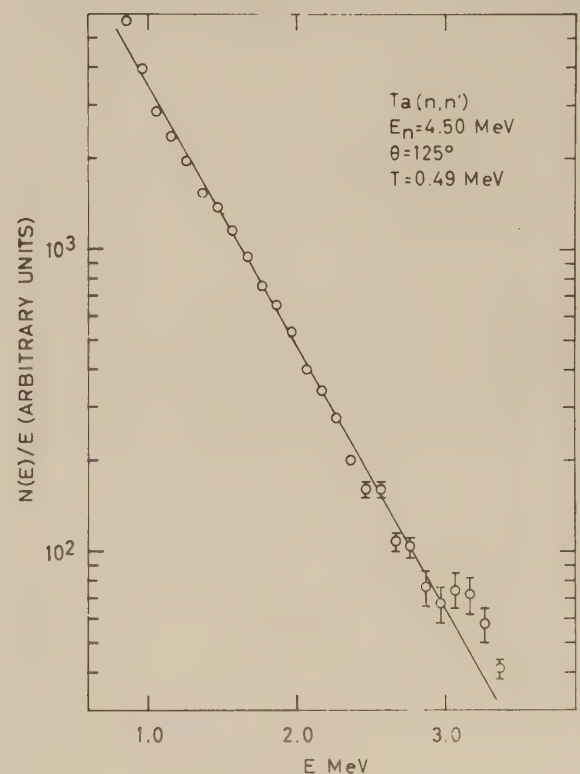


Fig 42. A plot of $\ln [N(E)/E]$ versus emitted neutron energy, E , for the inelastic scattering of 4.50 MeV neutrons from Ta.

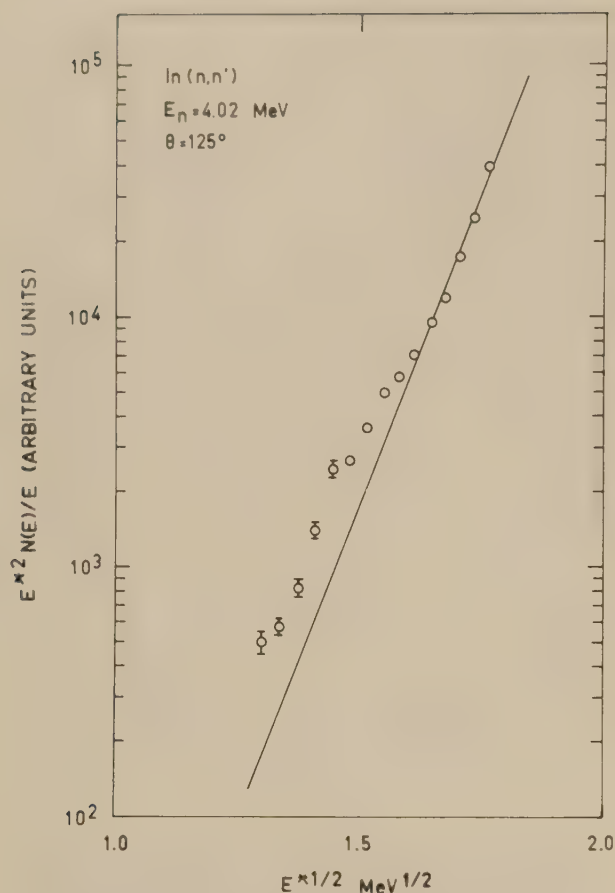


Fig 43. A plot of $\ln [E^2 N(E)/E]$ versus the square root of the excitation energy, $E^{1/2}$, for the inelastic scattering of 4.02 MeV neutrons from In.

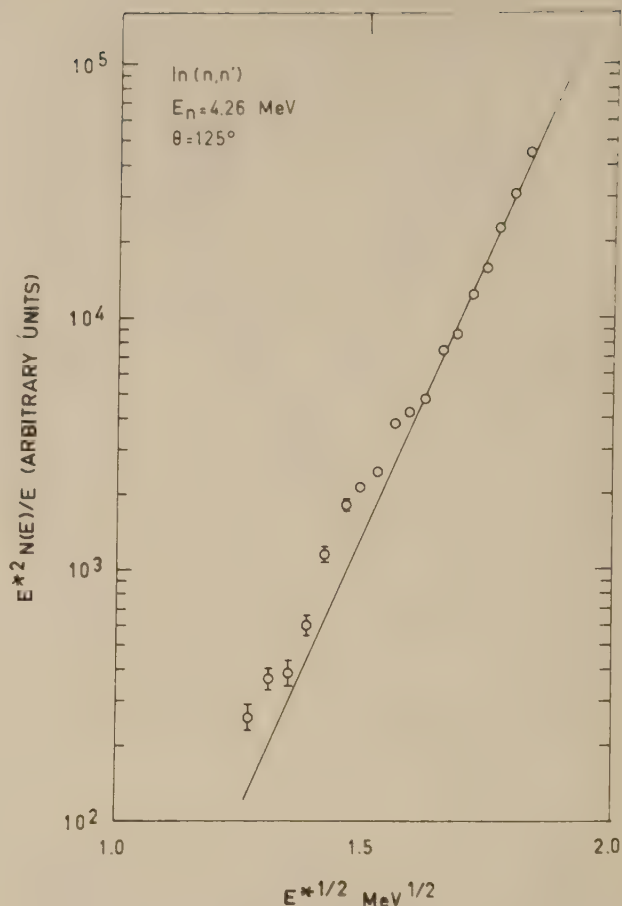


Fig 44. A plot of $\ln [E^2 N(E)/E]$ versus the square root of the excitation energy, $E^{1/2}$, for the inelastic scattering of 4.26 MeV neutrons from In.

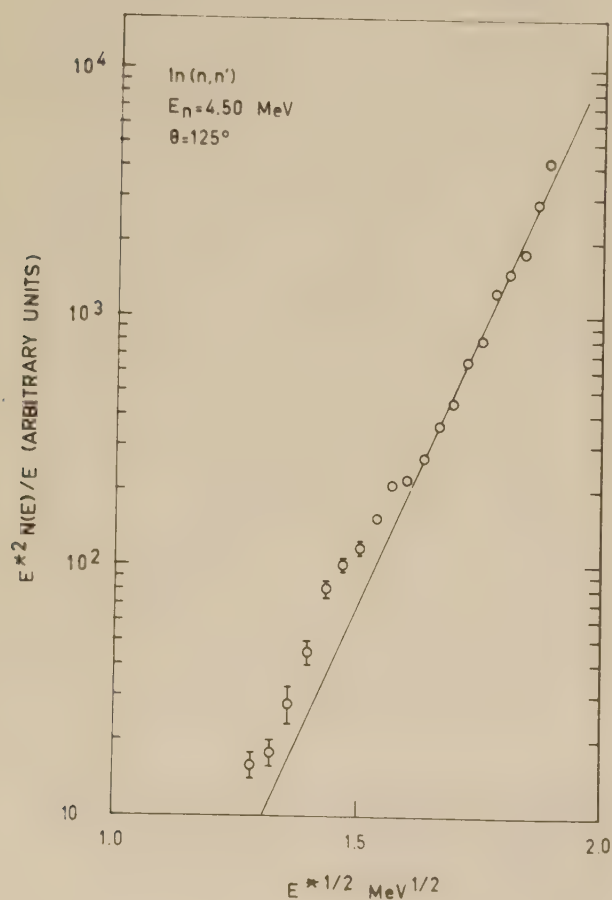


Fig 45. A plot of $\ln [E^2 N(E)/E]$ versus the square root of the excitation energy, $E^{1/2}$, for the inelastic scattering of 4.50 MeV neutrons from In.

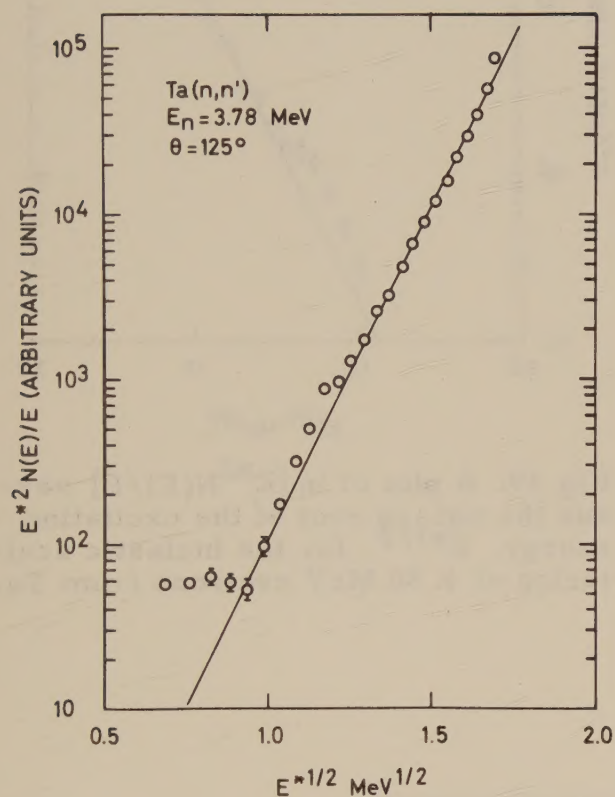


Fig 46. A plot of $\ln [E^2 N(E)/E]$ versus the square root of the excitation energy, $E^{1/2}$, for the inelastic scattering of 3.78 MeV neutrons from Ta.

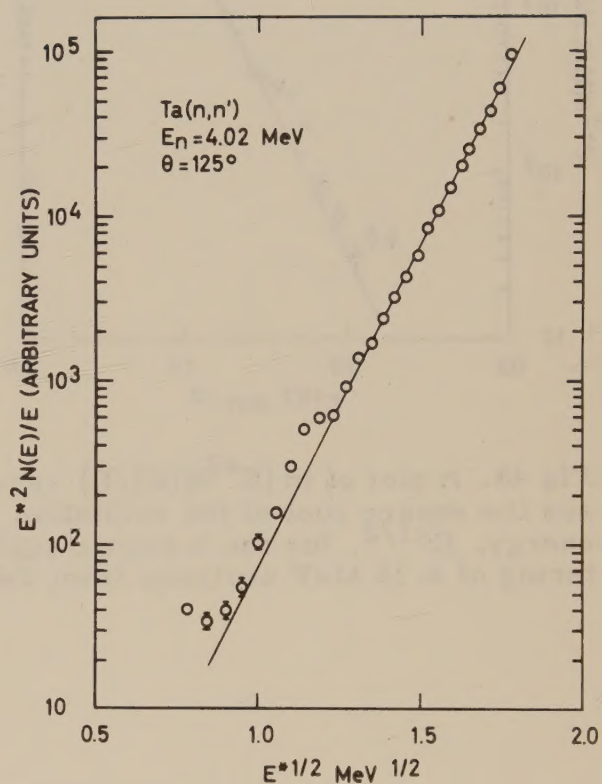


Fig 47. A plot of $\ln [E^2 N(E)/E]$ versus the square root of the excitation energy, $E^{1/2}$, for the inelastic scattering of 4.02 MeV neutrons from Ta.

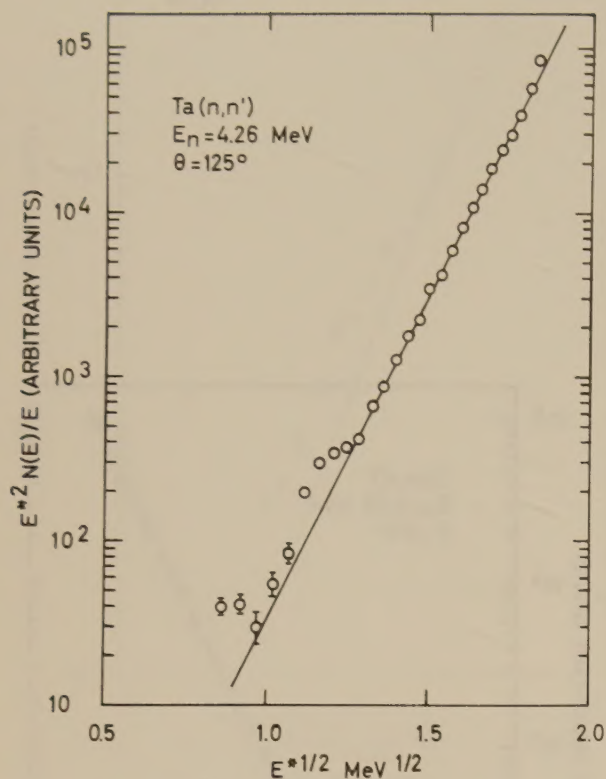


Fig 48. A plot of $\ln [E^{x2} N(E)/E]$ versus the square root of the excitation energy, $E^{x1/2}$, for the inelastic scattering of 4.26 MeV neutrons from Ta.

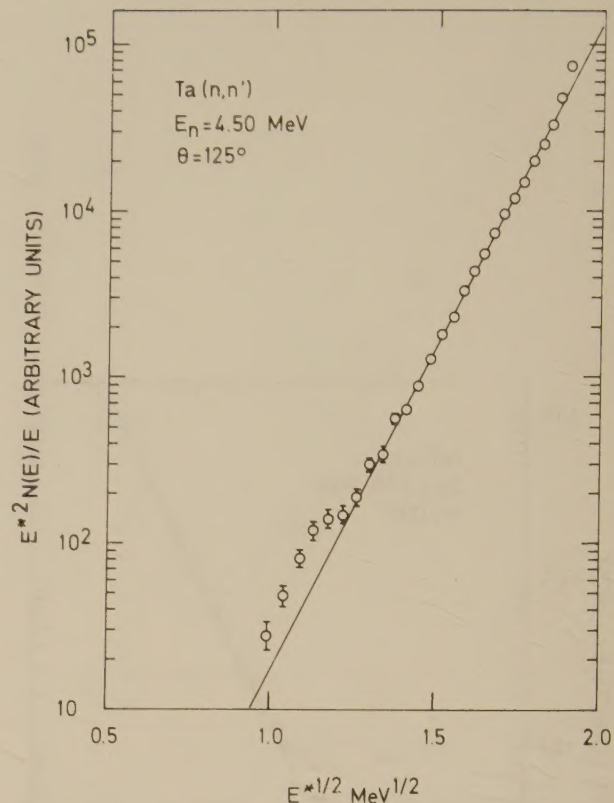


Fig 49. A plot of $\ln [E^{x2} N(E)/E]$ versus the square root of the excitation energy, $E^{x1/2}$, for the inelastic scattering of 4.50 MeV neutrons from Ta.

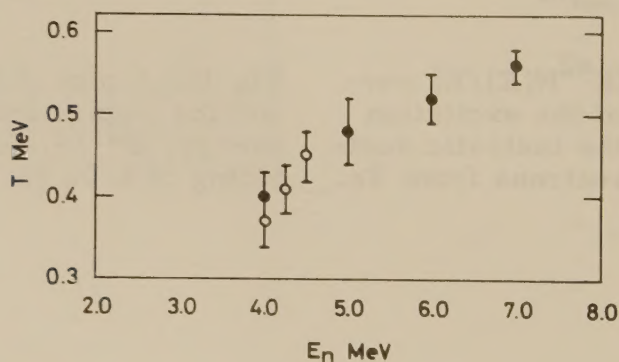


Fig 50. The values of the temperature parameter T obtained for In in the present work (unfilled circles) as well as those reported by Thomson [99] (filled circles).

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